THE Marquardt CORPORATION VAN NUYS, CALIFORNIA

HYPERGOLIC ENGINE SPACE POWER SYSTEM

Proposed Amendment to NAS 9-857-

RFP No. MSC BG 751-68-5-511P

VOLUME I - TECHNICAL

P. #1-1257

11 March 1965

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Modification II - Volume I

1.0 INTRODUCTION

The advantages of a space vehicle electrical power system which utilizes a prime mover of the internal combustion, reciprocating type capable of operation on liquid rocket engine propellants were recognized by The Marquardt Corporation early in the national space program. These advantages include a capability to closely approach an optimum thermodynamic cycle while maintaining reasonable component temperatures, the tremendous experience and "know-how" already existing for the conventional reciprocating engine, high reliability, and relatively low weight for the lower power output range. An awareness of these factors prompted Marquardt to initiate a company sponsored program late in 1957 which has culminated in the development of a prototype reciprocating engine incorporating most of the features necessary to permit its integration into an operational space system.

Although this engine has logged a significant amount of running time using hypergolic bipropellants as an energy source, its design is such that anyone of a large group of oxidizer-fuel combinations both liquid and gaseous may be employed by making minor alterations to the propellant injector system. Demonstration of the "multifuel" capability could be advantageous to NASA's space power program. Such a machine could reduce qualification requirements, through commonality, where dynamic power applications were desirable. With this in mind, a program to demonstrate operation of the space power unit on gaseous hydrogen and oxygen is proposed.

2.0 SUMMARY

2.1 TECHNICAL APPROACH

The proposed modification to the Phase II hypergolic engine program of operating the existing engine (SPU-2A-1) on gaseous H_2 and O_2 will constitute a separate program including the phases of analysis, design, fabrication and testing. The philosophy of the program will be the maximum utilization of existing components and test facilities, and the dependence on analysis for establishing the conditions of successful engine operation.

The engineering effort culminating in the feasibility demonstration of engine operation on gaseous H_2 and O_2 will be the result of successful solution of the following problems:

a. The utilization of the hypergolic injection mechanism for injection of propellants

b. The monitoring and control of gas flow

c. The method of ignition

d. The selection of injection sequences

2.2 PROGRAM PLAN

The seven week test program as planned, will result in the demonstration of feasibility, performance and endurance of a modified hypergolic ignition engine operating on hydrogen and oxygen. The work will be accomplished according to the following tasks.

Task 1 - Development Testing

Perform analysis and design changes as required to modify the SPU-2A-1 engine for hydrogen-oxygen operation.

Set-up, install, and test the modified engine incorporating ignition by catalytic action, and running a 25 to 50 hour continuous endurance run insofar as funding permits.

Task 2

Provide reports and documentation.

3.0 TECHNICAL DISCUSSION

3.1 STATUS

The feasibility of a hypergolic bipropellant reciprocating engine for use as a space power unit was demonstrated in a Phase I NASA sponsored program. The Phase I feasibility program was followed by a Phase II development program. During the Phase II program the adaptability of the hypergolic ignition engine configuration for operation on gaseous hydrogen and oxygen was considered. A preliminary evaluation indicated that the mechanical configuration and materials of construction were more than adequate for this application. However, analyses indicated that the injector valves were marginal in size for short dwell operation. In order to improve the injector valve configuration for operation on gaseous propellants the seat design was changed from a conical shape to a flat face configuration. This change increased the gain characteristics of the injector to allow higher flow rates for a given dwell period. Two valves were fabricated and dynamically tested with gaseous nitrogen. The valve system was sucessfully operated for a period of one hour at 2000 RPM, a ΔP of 1400 psi and 11° dwell. With the development of the SPU-3 hypergolic bipropellant recirpocating engine, the formerly used SPU-2A-1 engine will be available for use on this program. Minor design changes will be required for gaseous hydrogen and oxygen. However, the basic components of the engine such as cylinder, crankcase, crankshaft assembly and etc. will not require modification.

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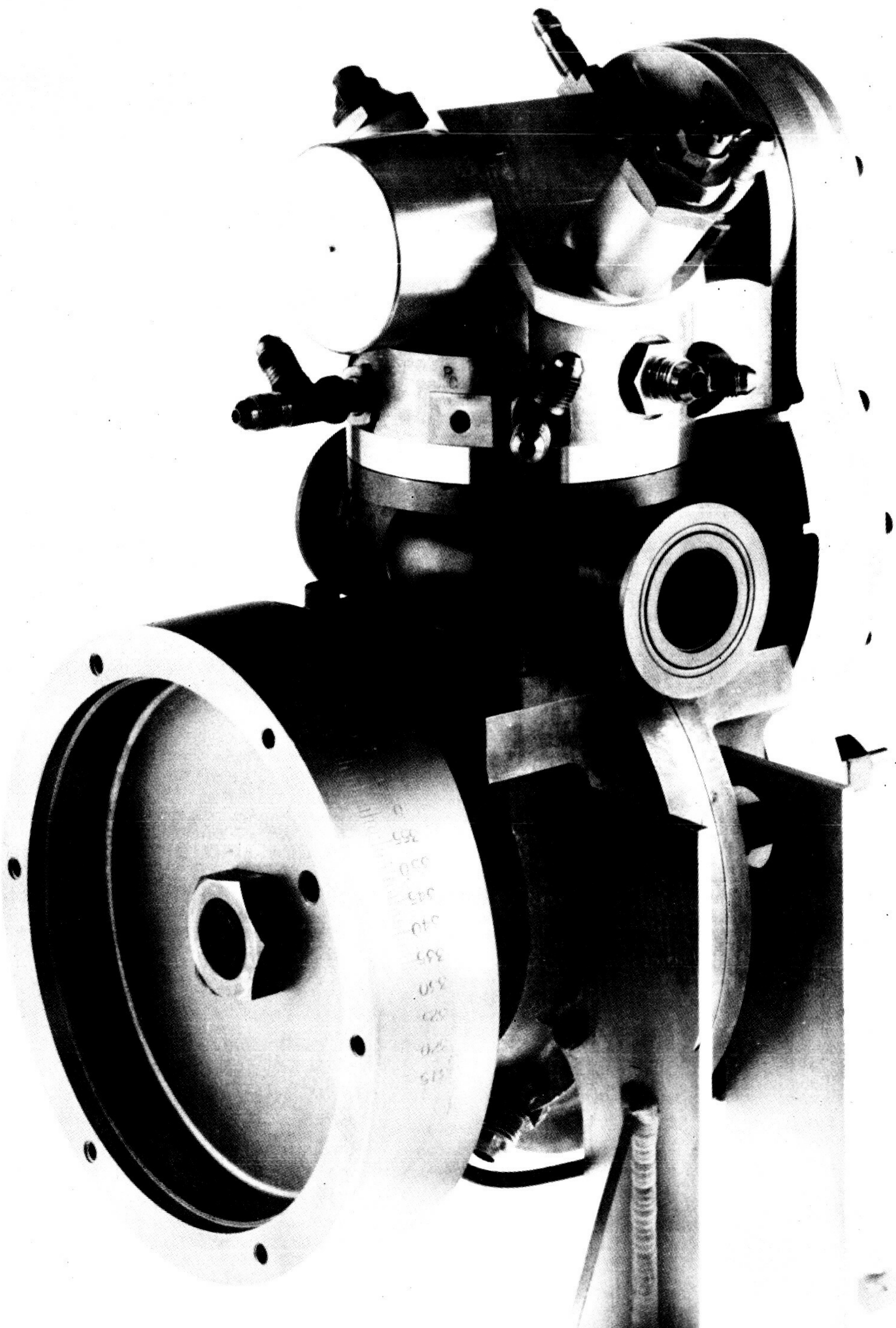
3.2 ENGINE

The engine used for operation on gaseous hydrogen and oxygen will be a modified SPU-2A-1 engine and will be identified as the SPU-2A-3 test engine. The external configuration of the SPU-2A-3 engine is identical to the SPU-2A-1.

The SPU-2A-3 engine is a single cylinder, liquid cooled, reciprocating unit capable of driving a 3KW electric generator (Figure 1 and 2). The engine is nominally rated at 4-1/2 hp at 4500 RPM. However, higher powers and rotative speeds are achievable for short durations. The engine will operate on metered injection of gaseous hydrogen fuel and gaseous oxygen as the oxidizer. The operating cycle is a modified Otto two-stroke cycle. The engine weighs approximately 30 lbs and occupies an envelope of 14 x 7 x 10 inches with no electrical generator installed. Most engine components are fabricated from corrosion resistant materials. Other engine components are fabricated from suitable materials consistent with high quality automotive engineering practice. Where applicable, well established high efficiency reciprocating engine design features within the present state of the art were used in formulating the design. Specific goals sought for establishment of the design were as follows:

- Minimum fabrication of new components.
- Completely adjustable propellant injection periods and timing.
- High overall engine efficiency, i.e., low specific propellant consumption.
- High engine and component reliability.

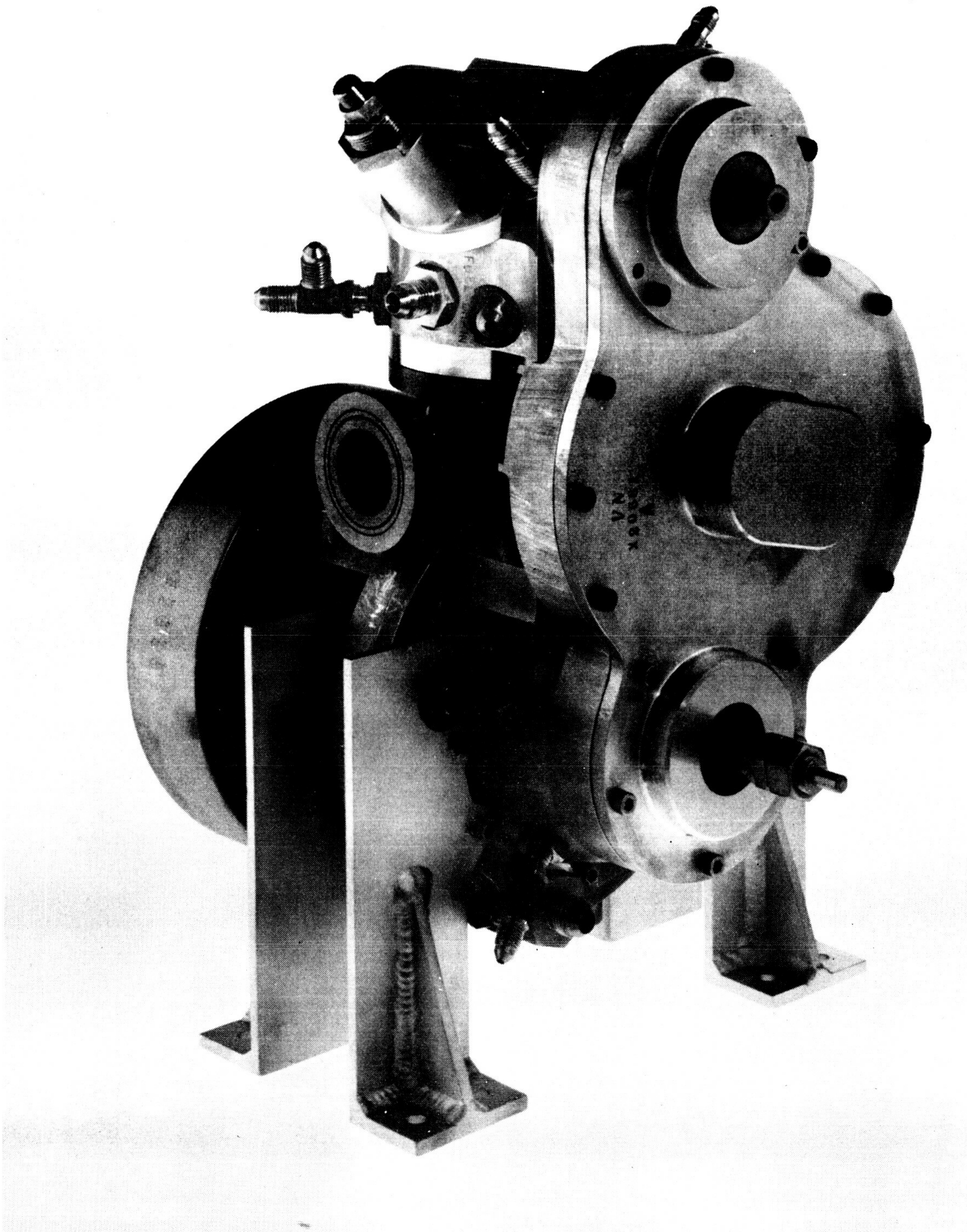
Since the engine design is primarily targeted at yielding design information and parametric test data for the hydrogen and oxygen fueled reciprocating space power generating system, certain subsidiary components considered secondary



NEG. T5134-20

SPU-2A-1 Engine

Figure 1



SPU-2A-1 Engine

NEG. T5134-19

in importance and possibly contributing to added cost and delay to the program were not included. These components include an oil pump, propellant pumps, water circulation pump, and starting system. These functions will be provided to the engine by the test facility and are equipped with external control and instrumentation to provide design criteria.

3.2.1 PROPELLANT INJECTION SYSTEM

A modification of the dual poppet Mono seat, short duration valve concept proved successful during the Phase I and Phase II programs of the hypergolic ignition reciprocating engine will be used in the gaseous hydrogen and oxygen engine. The valve modification consists of altering the seat design of the inner and outer valve components. These valves normally close on conical seats. This design will be changed to a flat faced valve configuration for oxygen and hydrogen operation. This modification provides a higher gain characteristic of the valve.

In addition to the change in the configuration of the valve seats, provisions will be made to lubricate the valve components continuously during engine operation. The same lubricant PR143 used on the hypergolic engine will also be used. Valve lubrication will be achieved by using the overboard drain ports normally required on the hypergolic ignition engine, to supply pressurized lubricants directly to the valve stems. Direct lubrication of the valve stems in conjunction with additional teflon seal rings will provide sealing of the gaseous oxygen and hydrogen from the valve chamber.

The SPU-2A-3 engine will utilize the camshaft configuration design of the SPU-3 hypergolic ignition engine. This configuration features individual cam lobes indexed to a common shaft with keys. This allows each propellant injector to be timed independently for dwell and start of injection. The flexibility of this design will allow optimization of hydrogen and oxygen injection periods and dwell without the necessity of fabricating additional components.

3.2.2 PISTON AND PISTON RINGS

The operating cycle and environment within the hydrogen and oxygen engine are particularly severe on piston and piston rings. The most successful piston design developed to date in the hypergolic ignition reciprocating engine has been of a composite configuration. This design consists of a Rene'41 or alternately an N155 alloy crown and a D132 cast aluminum skirt section. The crown materials were selected to withstand conditions of high temperature, high pressure environment. The skirt material, was selected for its excellent gearing and heat transfer characteristics. The top piston ring assembly is carried in a groove of the crown and rests on the aluminum skirt. The second and third ring assemblies are carried completely in the aluminum skirt slightly below the skirt crown interface. This piston configuration is shown in Figure 3. The ring assemblies themselves are of unique design, consisting of a three-piece interlocking configuration having two outer rings and a backup inner ring. This configuration offers the following major advantages:

- Positive end gap sealing.
- Low leakage at high pressures.
- Low wall tension.
- Positive constraint of ring ends (cannot spring into exhaust ports reducing possibility of breakage).

HI-BMEP PISTON

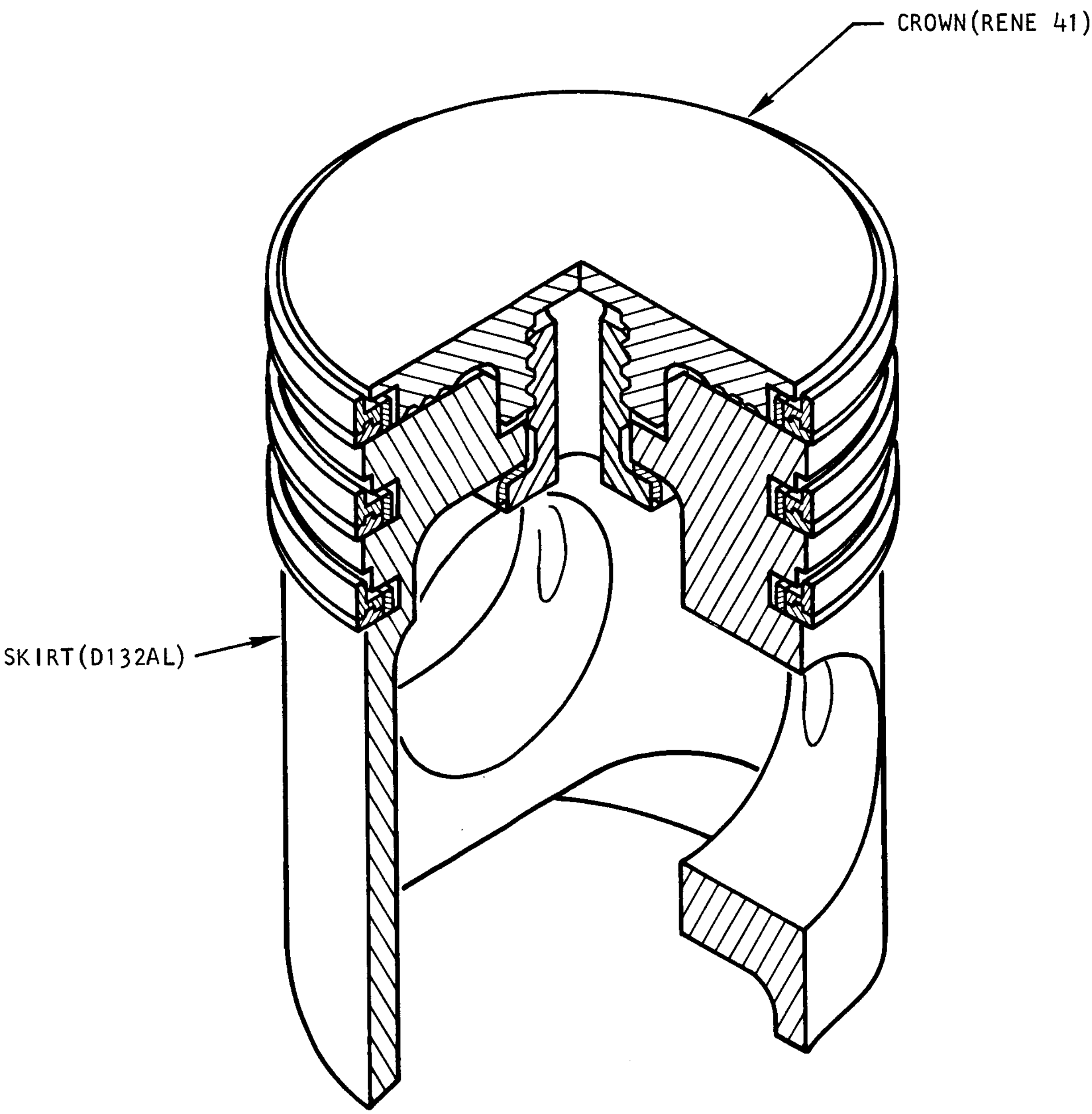


Figure 3

- Eliminates pinning of rings.
- Improved mechanical strength.

3.2.3 LUBRICATION

The crankcase and crankshaft assembly of the SPU-2A-3 is designed for maximum strength and durability commensurate with a test engine configuration. The single throw crankshaft is supported in two sleeve bearings machined integrally in the aluminum crankcase section. The connecting rod is also of a sleeve bearing design. Oil is fed to the main bearings and the connecting rod bearing under pressure by a pump located externally and is part of the test facility. The cylinder, piston, and wrist pin assembly are lubricated by splash oil from the connecting rod. The camshaft and rocker arm assemblies located in the cylinder head are also lubricated by pressurized oil from the facility pump.

3.2.4 IGNITION SOURCE

A catalytic ignition source has been selected for use in the SPU-2A-3 engine. The catalytic agent will be active platinum particles constrained within a 200 mesh nickel wire cage. This installation is shown in Figure 4 . Active platinum was selected as the ignition source because of the success the ASTRO division of TMC has experienced with this material during their Oxygen/Hydrogen ignition studies (NAS Contract No. 8-11250). Repeated ignitions of O_2 and H_2 over a period of several weeks with the same catalyst under conditions far more adverse than would be experienced within the SPU-2A-3 combustion chamber, were decisive factors in the selection of a catalyst ignition source and active platinum specifically.

CATALYST INSTALLATION

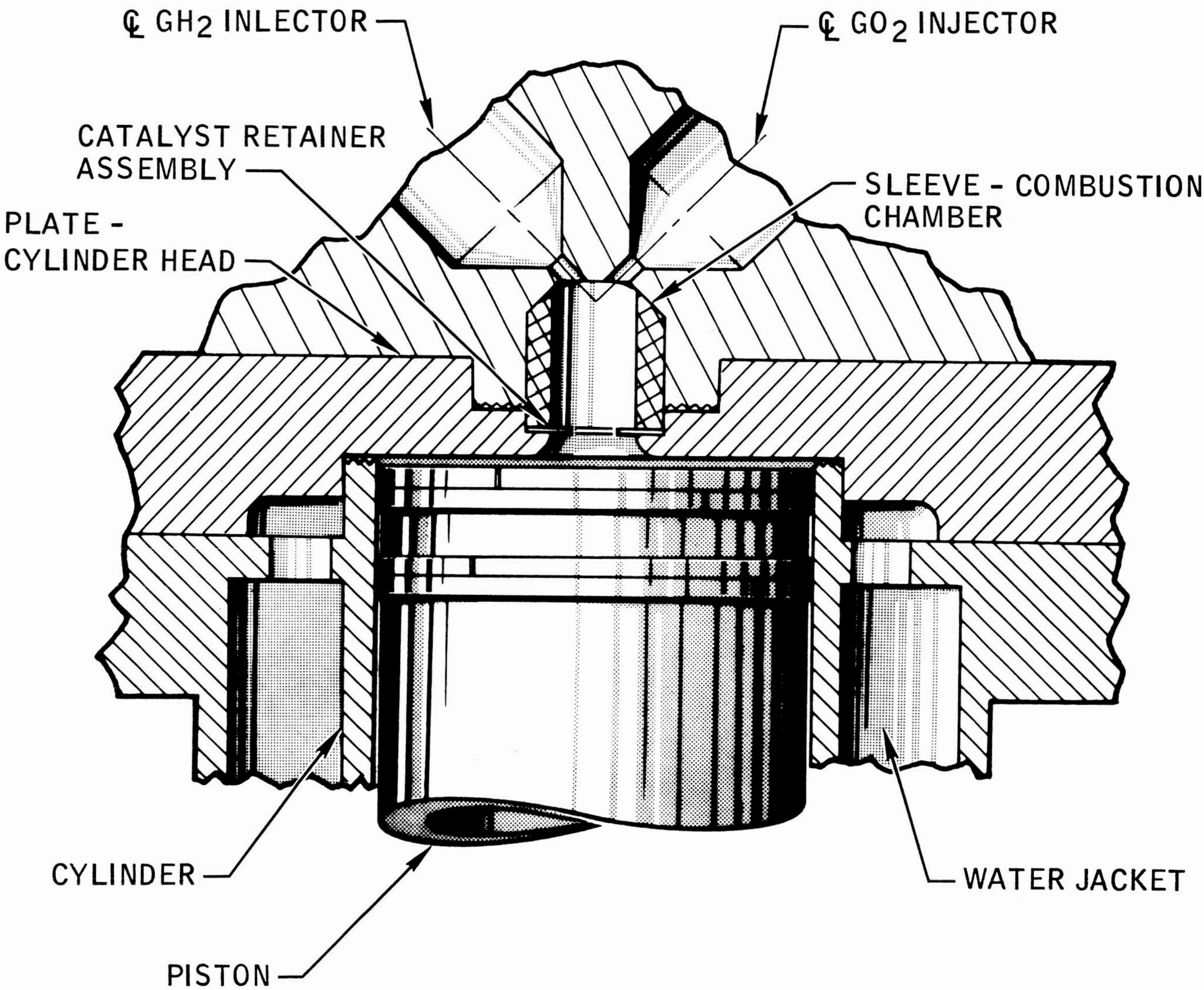


Figure 4

Other methods of ignition such as spark plug, glow plug, and auto ignition (diesel compression ignition) were considered.

Each of these systems have merit and will be given additional study. It was, however, deemed desirable to utilize and ignition system of proven capability for the feasibility test program thus minimizing unknowns and reduce system complexity.

3.3 ANALYSIS

The following investigation was conducted to verify the concept feasibility of operating the hypergolic propellant engine on gaseous oxygen and hydrogen.

Engine operating temperature and pressure limits were restricted to those values obtained in the hypergolic ignition engine operating at 200 psi BMEP and stoichiometric propellant mixture (O/F) conditions.

The analysis presents the guidelines with which to modify the necessary components and to establish values to select engine settings such as injection timing dwell, injection pressures, O/F ratios, and expansion ratios.

3.3.1 SUMMARY

The SPU-2A engine is capable of operation on H_2 and O_2 propellants from a thermodynamics standpoint. BSPC values of 1.3 are calculated for a 36:1 expansion ratio engine operating at an O/F ratio of 5.3. Propellant supply pressure dwell angle schedules are well within the useful operating range.

Major problem areas anticipated are combustion efficiency and stratification.

3.3.2 BASIC THERMODYNAMICS OF H_2-O_2 CYCLES

Figure 5 shows specific propellant consumption for H_2 - O_2 engines versus O/F for various thermal efficiencies. Several pertinent factors are apparent from this Figure. For a constant thermal efficiency, SPC decreases as O/F increases. SPC decreases when O/F ratio is held constant as thermal efficiency increases.

Although thermal efficiency is a function of expansion ratio for Otto cycle engines, improved system performance is achieved by designing for higher temperatures throughout the engine cycle. If the temperature after expansion (and prior to blowdown) is assumed a design constant, then as expansion ratio increases, the combustion temperature increases. As combustion temperature increases, the O/F ratio increases and the BSPC is reduced, as illustrated in Figure 5

As O/F ratio increases, the H_2 required is reduced and the excessive penalty for H_2 tankage is reduced in a flight system. This effect is illustrated in Figures 6 and 7 . Figure 6 shows the ratio of tank weight to propellant weight as a function of O/F ratio. Note that as O/F ratio increases, the tankage weight decreases. Thus, there is incentive for operating as near stoichiometric as possible. Figure 7 shows a constant weight line overlaid on the information from Figure 5 . From a systems standpoint, operation at a higher

GENERALIZED PERFORMANCE

H_2 - O_2 ENGINES

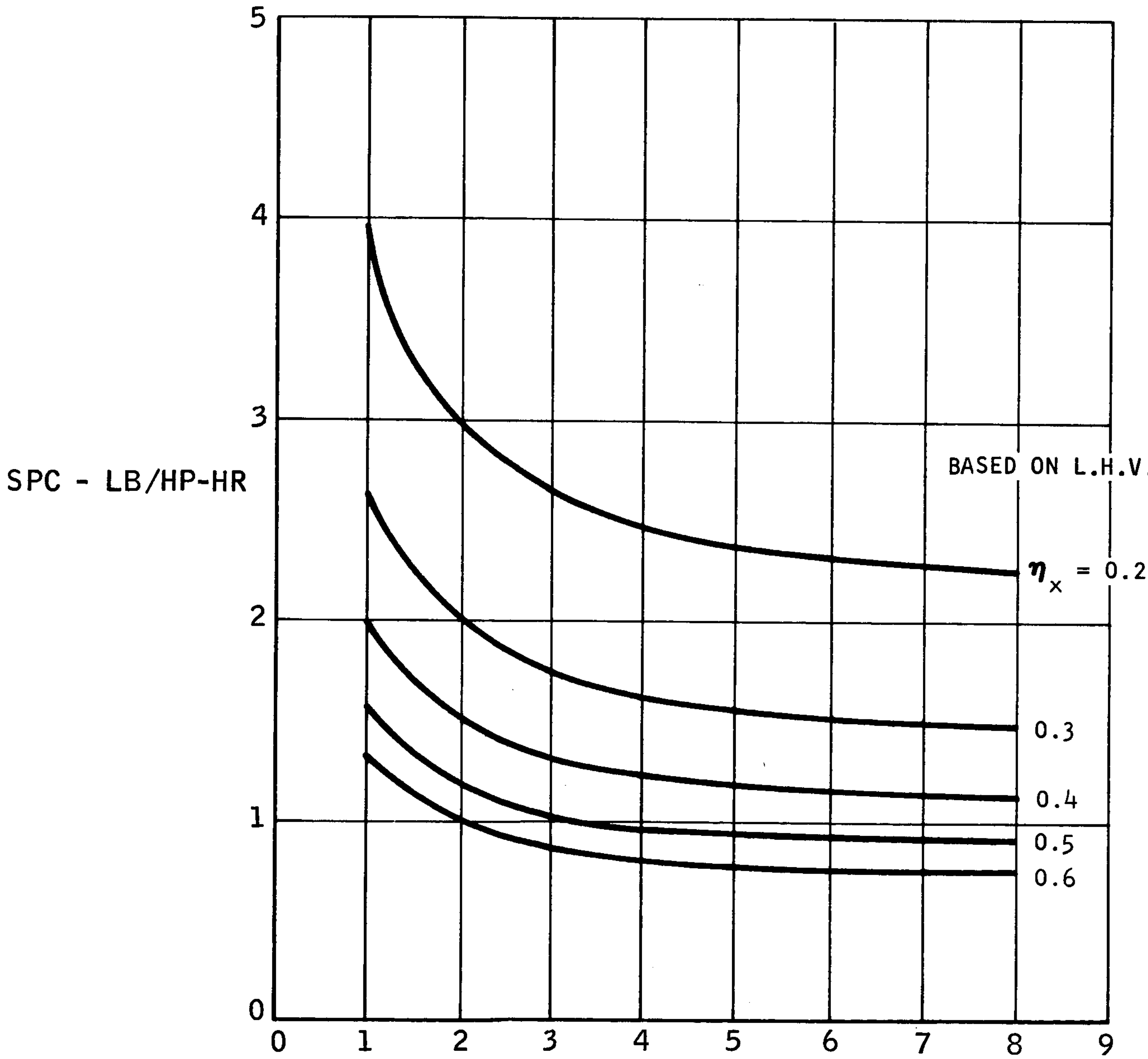


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Figure 5

SUPERCRITICAL TANKAGE WEIGHT FOR $H_2 - O_2$ SYSTEMS

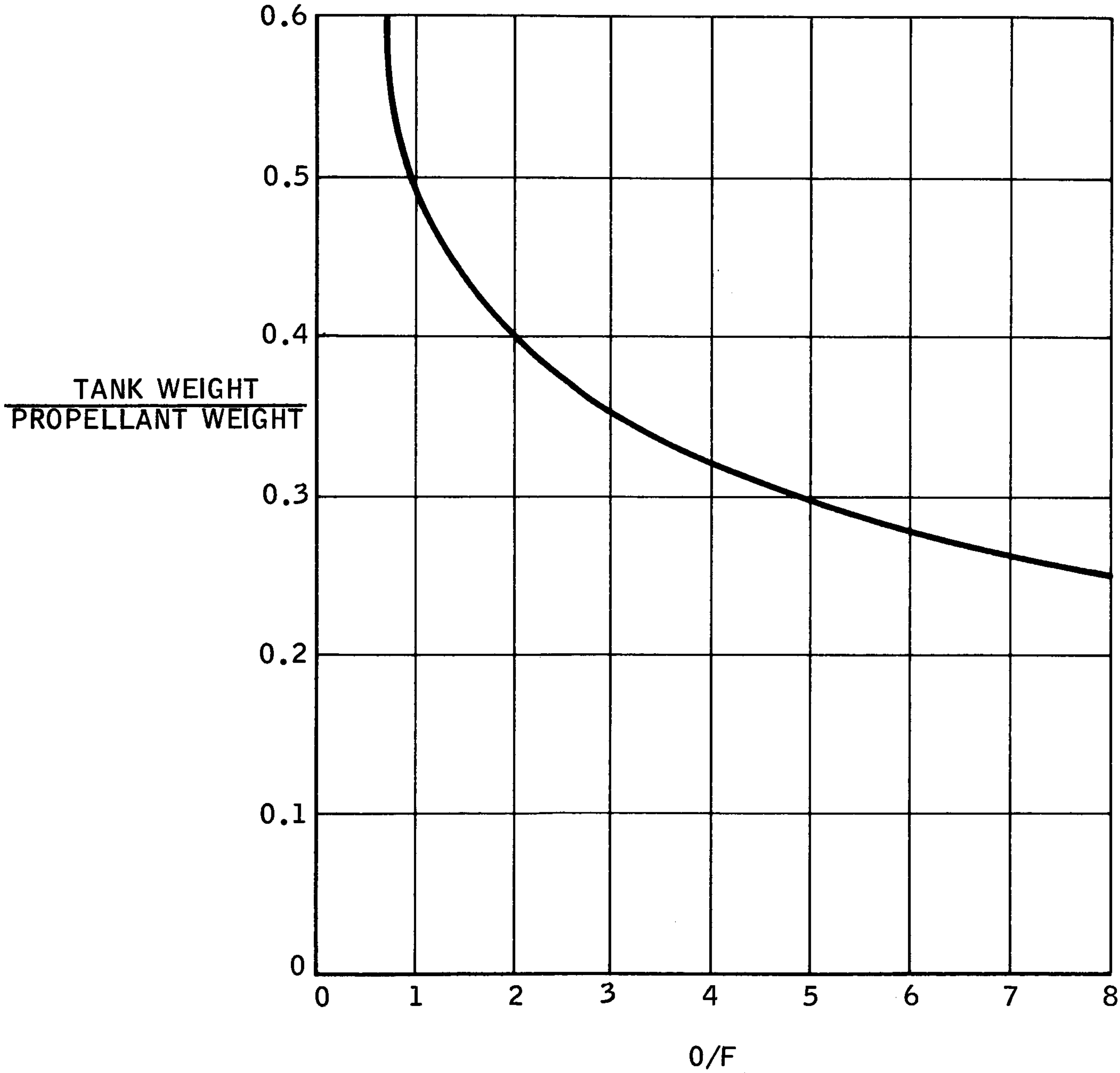

Figure 6

SYSTEMS WEIGHT COMPARISONS FOR $H_2 \cdot O_2$ SPU'S

(NO BOILOFF ASSUMED)

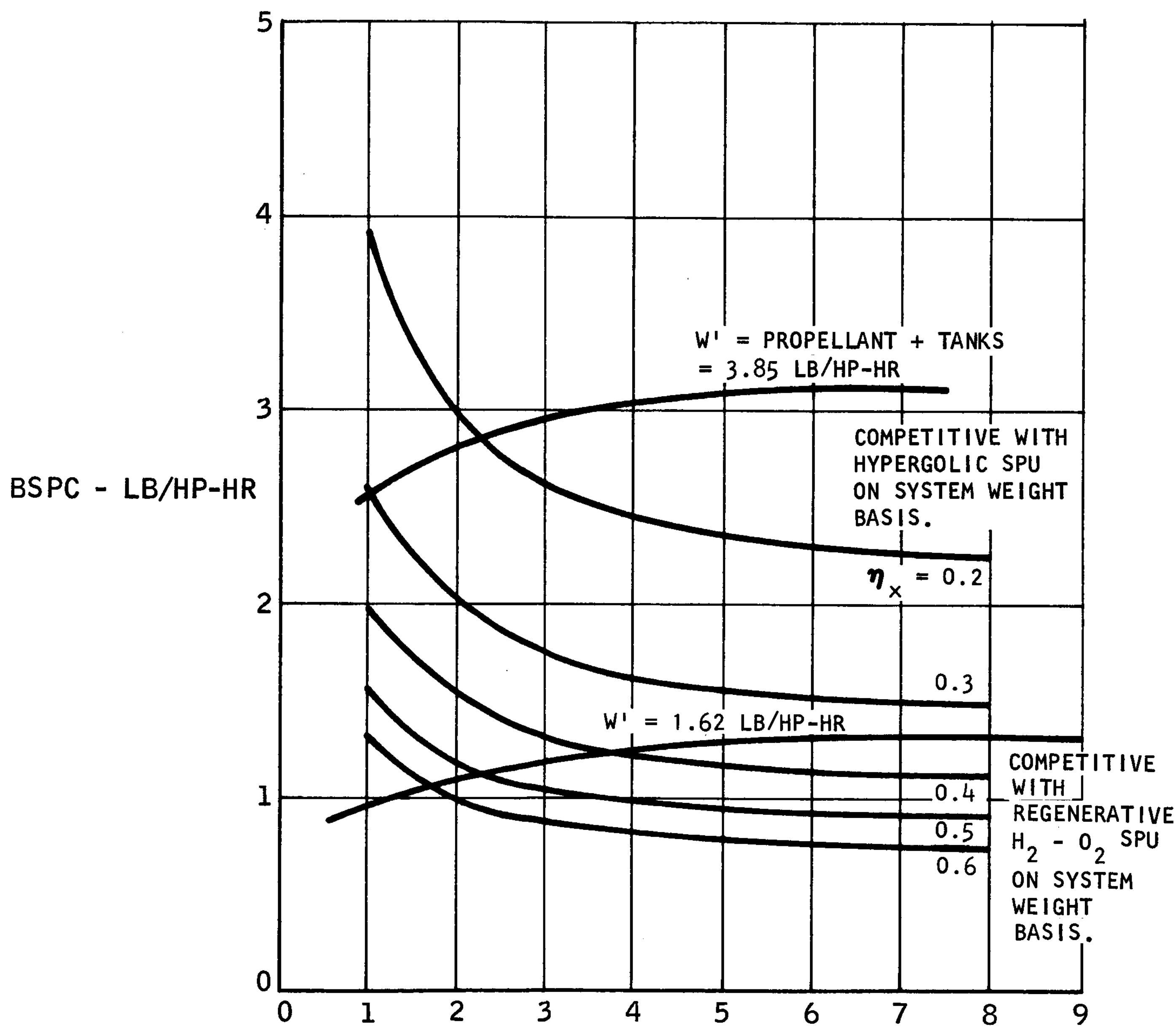

Figure 7

O/F ratio, may be attractive. With the higher O/F ratio there is however less heat sink in the incoming propellants for SPU cooling.

The propellant consumption of an engine varies inversely with the thermal efficiency of the engine cycle. The ideal thermal efficiency of an Otto cycle is a function only of the expansion ratio of the engine. However, this ideal efficiency is reduced with heat rejection, leakage and other deleterious effects. Figure 8 illustrates the effect on thermal efficiency of heat rejection. The heat rejection is expressed as a fraction of the shaft power output in equivalent units. Three parameter lines are shown for various values of Y. Y is an algebraic weighting factor pertaining to the distribution of heat rejection in the cycle. A value of Y = 0 implies that all heat is rejected at the beginning of an expansion stroke, and a value of Y = 1 implies all the heat is rejected during and after blowdown. The Y = 0 assumption is probably too severe, and Y = 1 is unduly optimistic. Thus, the value of Y is somewhere between 0 and 1. A Y value of .6 appears to be consistent with automotive engine test experience and is used in this analysis to access the effects of heat transfer on thermal efficiency.

3.3.3 H_2-O_2 ENGINE OPERATING CHARACTERISTICS

The characteristics of the SPU-2A engine operating on H_2 and O_2 were computed to determine (1) engine operating parameters, (2) propellant supply conditions, and (3) effects of operating variables.

The previous discussion indicated the desirability of operating at high cycle temperatures. To determine the maximum allowable cycle temperature and other associated parameters, operation of the SPU-2A engine with hypergolic propellants was used as the limiting criteria. Assuming a Q/HP = 1.5 and an expansion ratio of 36, the temperature at the end of the expansion stroke is

EFFECT OF HEAT REJECTION ON THERMAL EFFICIENCY

(CONSTANT EXHAUST TEMPERATURE ASSUMED)

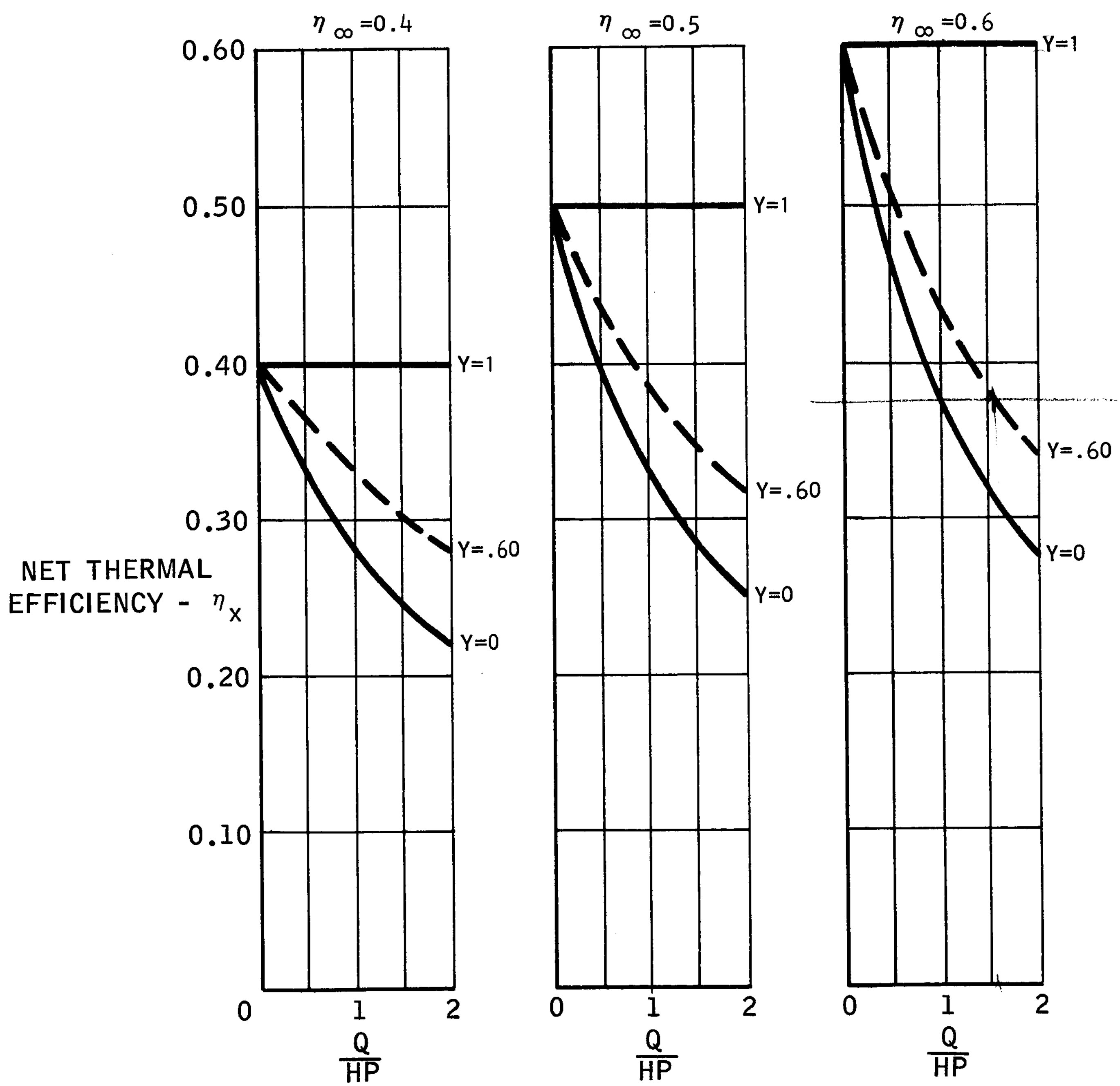

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Figure 8

computed to be 2240°R. This design point temperature is maintained for H_2 - O_2 operation. The maximum cycle temperature can be computed using the ideal thermal efficiency, η_∞, which is a function of the expansion ratio. The propellant consumption characteristics must be determined by using the actual thermal efficiency of the cycle. The actual thermal efficiency η_x is obtained by correcting η_∞ for heat, friction and leakage losses.

Figure 9 illustrates the maximum cycle temperature, O/F ratios with and without heat transfer and BSPC values with and without heat transfer.

At this point it is worthwhile to introduce a concept which applies to engines operating at less than stoichiometric O/F ratio. To facilitate the understanding of the combustion process, a "heating" value of oxidizer is introduced. It is more convenient to treat the oxidizer as the heat source rather than the fuel, because all the fuel is not combusted but all the oxidizer does react. For the H_2 - O_2 propellant combination, a "heating" value for O_2 is 6440 BTU's/lb (LHV).

Another concept which must be explained is, that for a given expansion ratio engine, the amount of H_2 required is practically independent of thermal efficiency. In engines working with H_2 - O_2 propellants, the partial pressure of H_2 is doing the majority of the work, and the O_2 serves primarily as the heat source. Thus, in an engine when the effects of heat transfer are known and the decrease in thermal efficiency noted, the increased propellant consumption is all O_2, since the O_2 alone delivers the heat for rejection. The ideal O/F ratio more nearly reflects the O/F ratio required to produce power, while the actual O/F ratio is indicative of the propellant requirements for power and heat rejection.

Returning to Figure 9 , it can be seen that the O/F ratio increases rapidly as the expansion ratio increases. The BSPC decreases as the expansion ratio increases, as would be expected. The BSPC values shown for the Q/HP = 1.5 assumption is considered attainable in the current test program.

H_2 - O_2 ENGINE PERFORMANCE WITH & WITHOUT HEAT REJECTION

(NON REGENERATIVE)

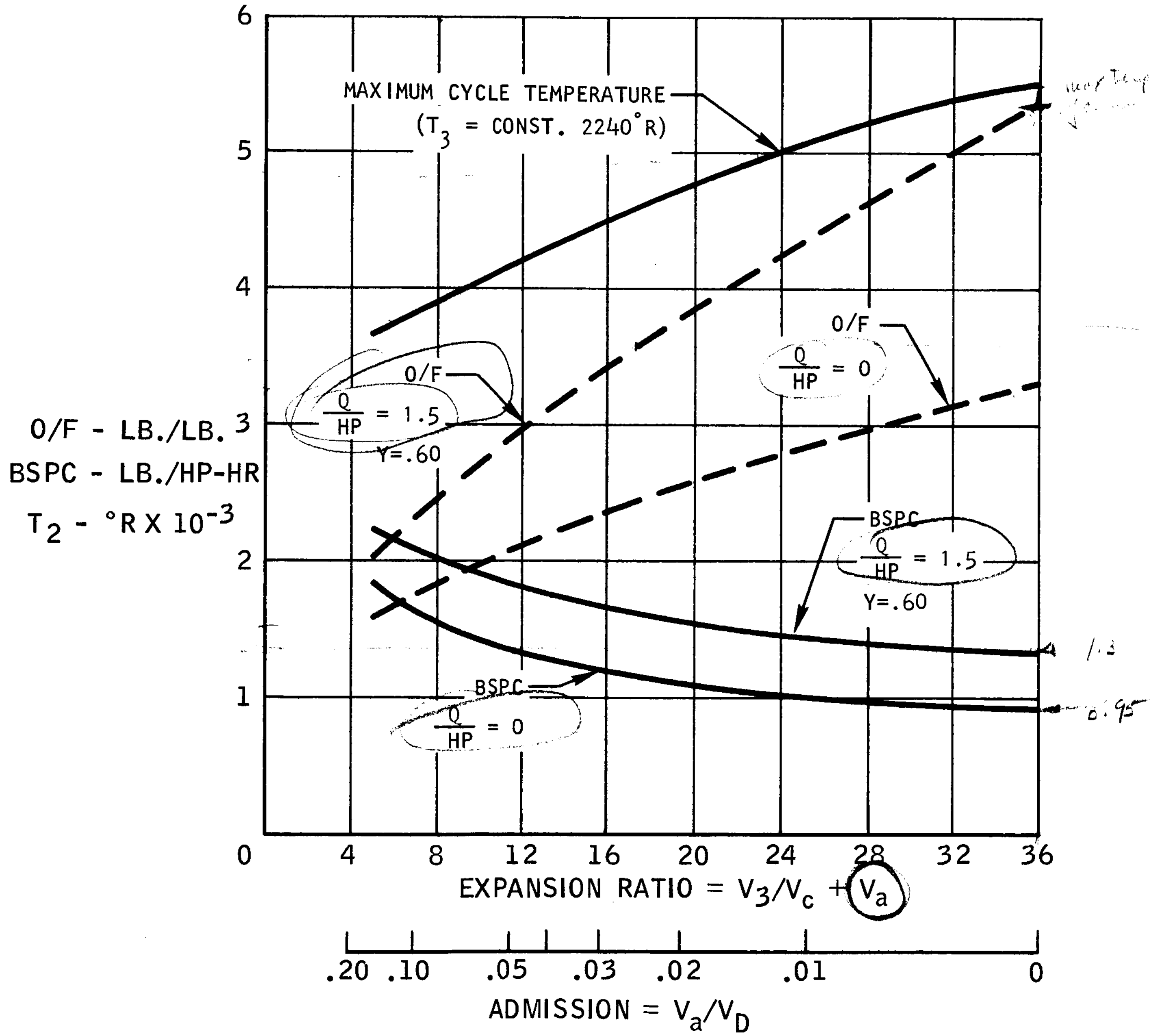

Figure 9

The basic design point for the engine is a BMEP of 200 psi at 3000 RPM, which is 3.69 HP. The engine performance and propellant supply characteristics at a BMEP of 200 were computed, and characteristics at other BMEP's can be ratioed linearily. (An assumption of constant FMEP is implied and justified when the other required assumptions are rationalized.)

Figure 10 shows the ratio of BMEP/P_2 as a function of expansion ratio. Also shown are curves indicating how P_2 decreases as expansion ratio decreases. These curves illustrate the point that, for an engine stressed for a certain maximum pressure, the specific power output (HP/cubic inch of displacement) increases as expansion ratio decreases. However, thermal efficiency decreases, and imposes a flight system weight penalty for long duration missions.

Figure 11 shows an indicator diagram for an idealized Otto cycle operating in vacuum. The peak pressure in the cycle is related to the propellant pressure prior to combustion by the relation for a constant volume process.

$$\frac{P_2}{P_1} = \frac{T_2}{T_1} = \frac{T_1 + \Delta T_c}{T_1}$$

ΔT_c is a function of O/F ratio and is illustrated in Figure 12. The O/F ratio used for this calculation is the O/F ratio actually producing work (viz: O/F when Q = 0; see Figure 9) . For computing P_1 at any given expansion ratio (or admission ratio), the O/F is known (from Figure 9) and the ΔT_c is determined from Figure 12. . T_1 is mearly the supply temperature of H_2 corrected for residual gas mixing and any Joule-Thomson throttling losses. After T_1 and ΔT_c are known and P_2/P_1 ratio is determined, P_1 can be calculated since P_2 is known from Figure 10 . P_1 versus expansion is shown in Figure 13.

BMEP & PEAK PRESSURES VS EXPANSION RATIO

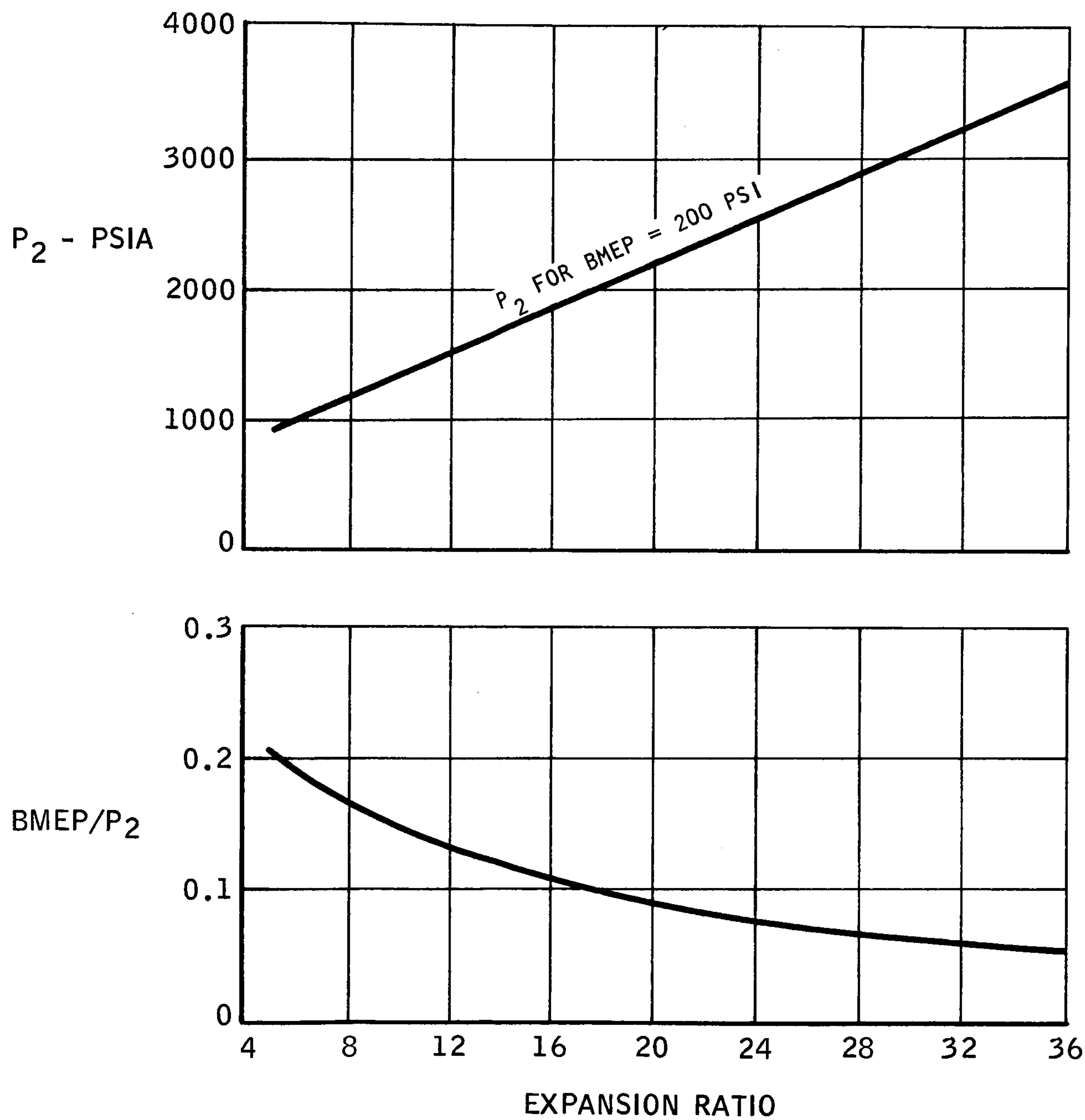

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Figure 10

INDICATOR DIAGRAM FOR MODIFIED OTTO CYCLE

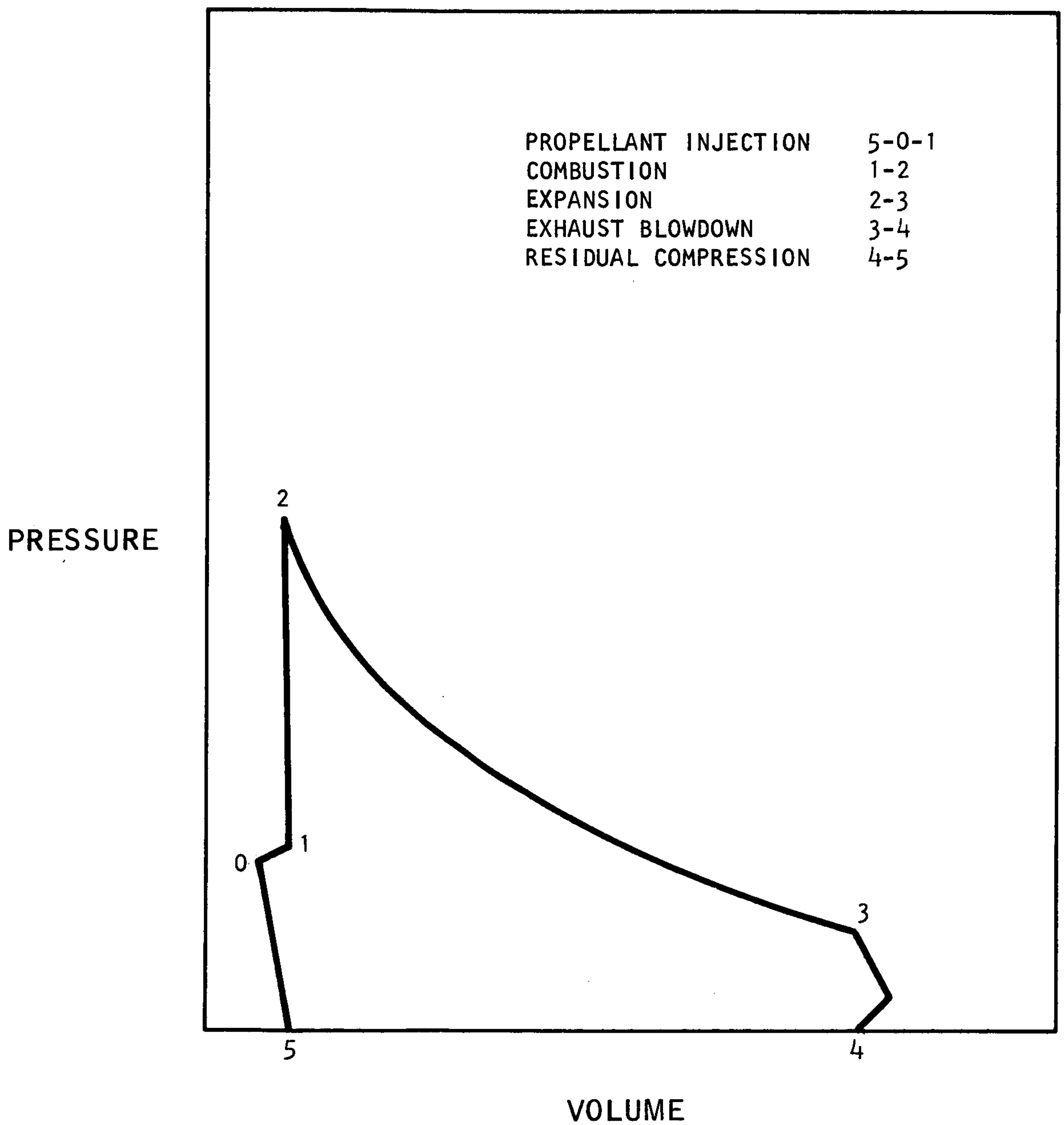

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Figure 11

TEMPERATURE RISE AT CONSTANT VOLUME FOR MIXTURES OF H_2 & O_2

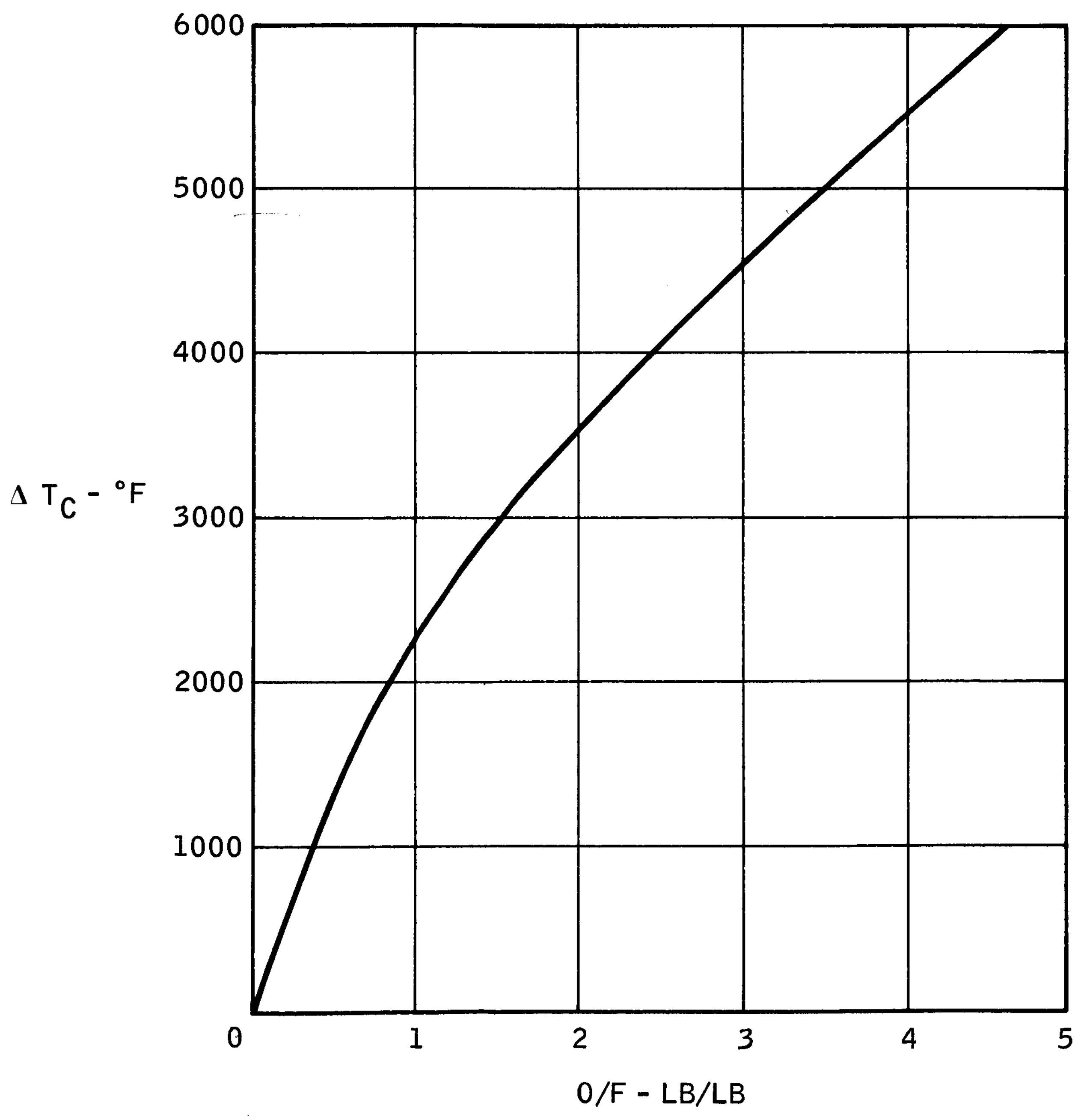

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Figure 12

PRE COMBUSTION PRESSURE AT BMEP = 200 PSI

(NON REGENERATIVE)

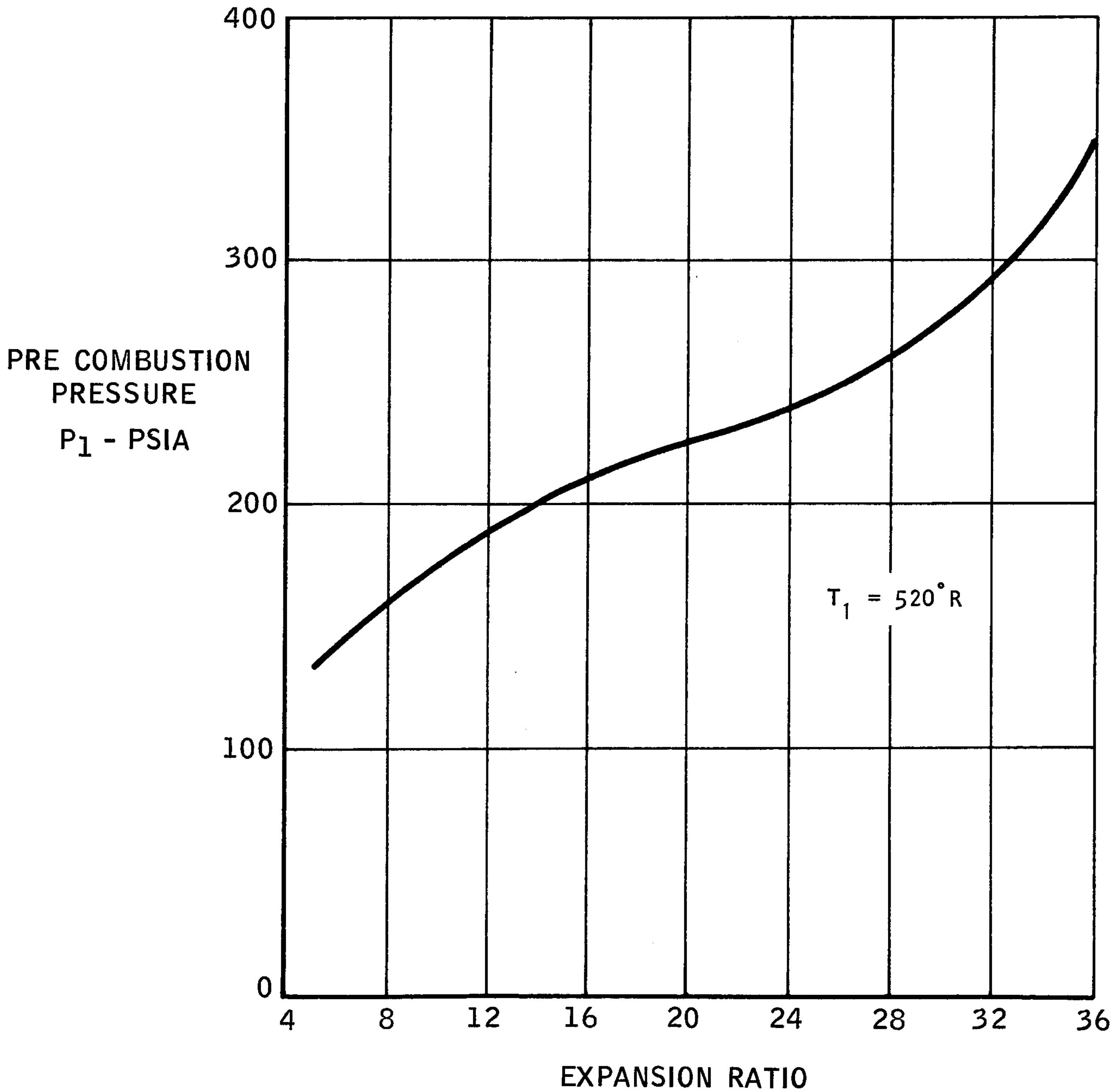

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Figure 13

The pressure P_1, prior to combustion, is the sum of the partial pressures of H_2 and O_2. The majority of the pressure is contributed by the H_2. The exact relation between H_2 partial pressure and P_1 is

$$\frac{P_{H_2}}{P_1} = \frac{1}{1 + 1/16 \ O/F}$$

This relation is plotted in Figure 14.

Thus, by using Figures 13 and 14 and O/F information from Figure 9 , the maximum pressure of H_2 prior to O_2 injection is evaluated.

3.3.4 PROPELLANT SUPPLY CONDITIONS

Admission of H_2 and O_2 propellants into the SPU-2A engine must be treated as an injection problem rather than a "breathing" problem, as in air breathing engines. The propellant supply pressures required were computed assuming sonic flow through the dual concentric poppet valves at various dwell (flow periods) angles. A discharge coefficient of 0.6 was assumed for all calculations, which is conservative. The supply pressures for the two propellants were computed for BMEP of 200 psi. Supply pressures at other BMEP's can be determined by ratioing linearly from the BMEP = 200 psi condition. Propellant pressures were determined for dwell angles from 5 to 30° and for expansion ratios from 5 to 36.

The O_2 supply pressures calculated are shown in Figure 15. This curve shows that the propellant pressure increases as the dwell angle becomes shorter. The supply pressure for a given dwell angle decreases with expansion ratio because of the lower O_2 flow stemming from the increased thermal efficiency.

PARTIAL PRESSURE OF H_2 IN H_2 & O_2 MIXTURES

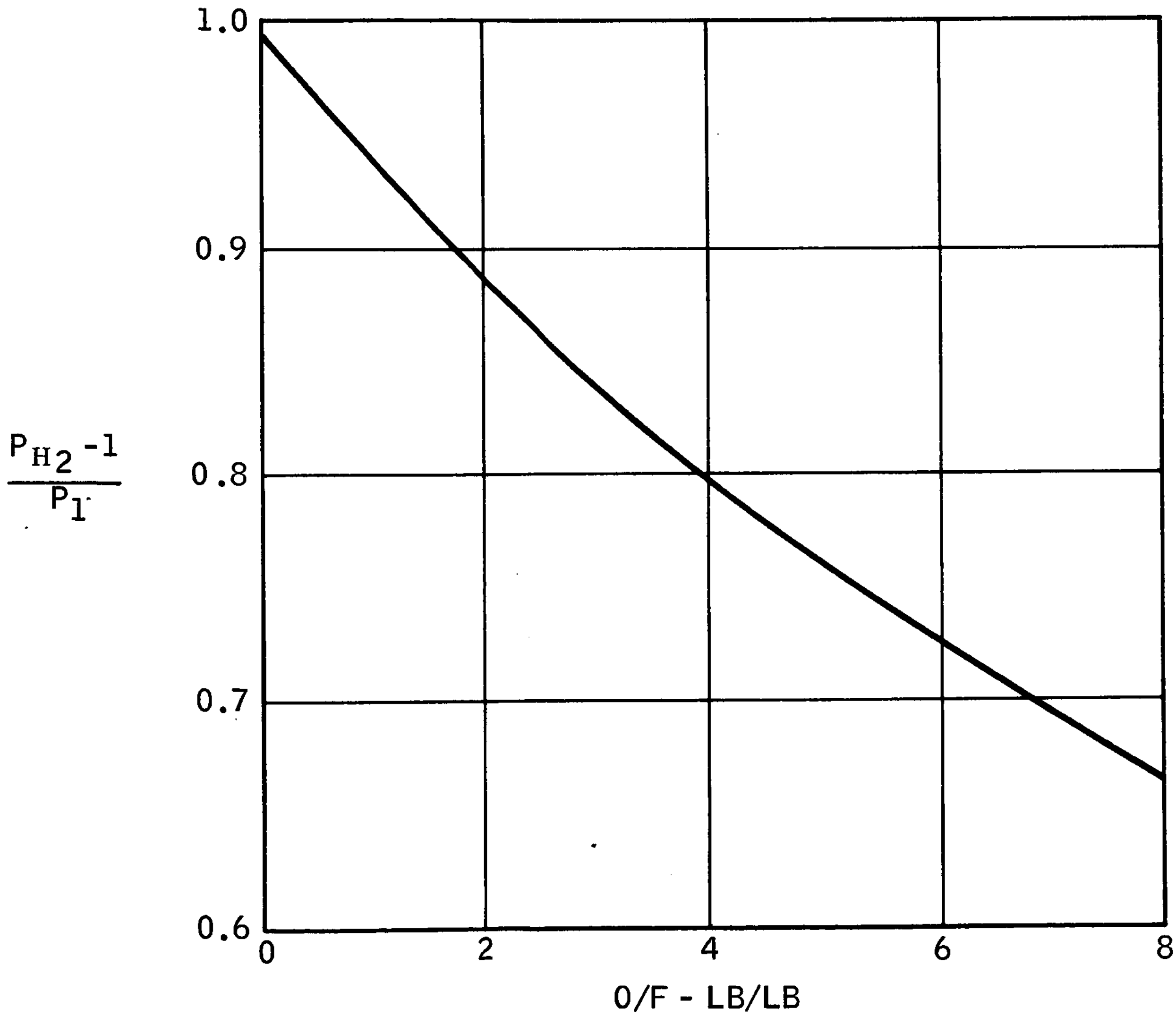

Figure 14

OXYGEN SUPPLY PRESSURE FOR BMEP = 200 PSI & 3000 RPM

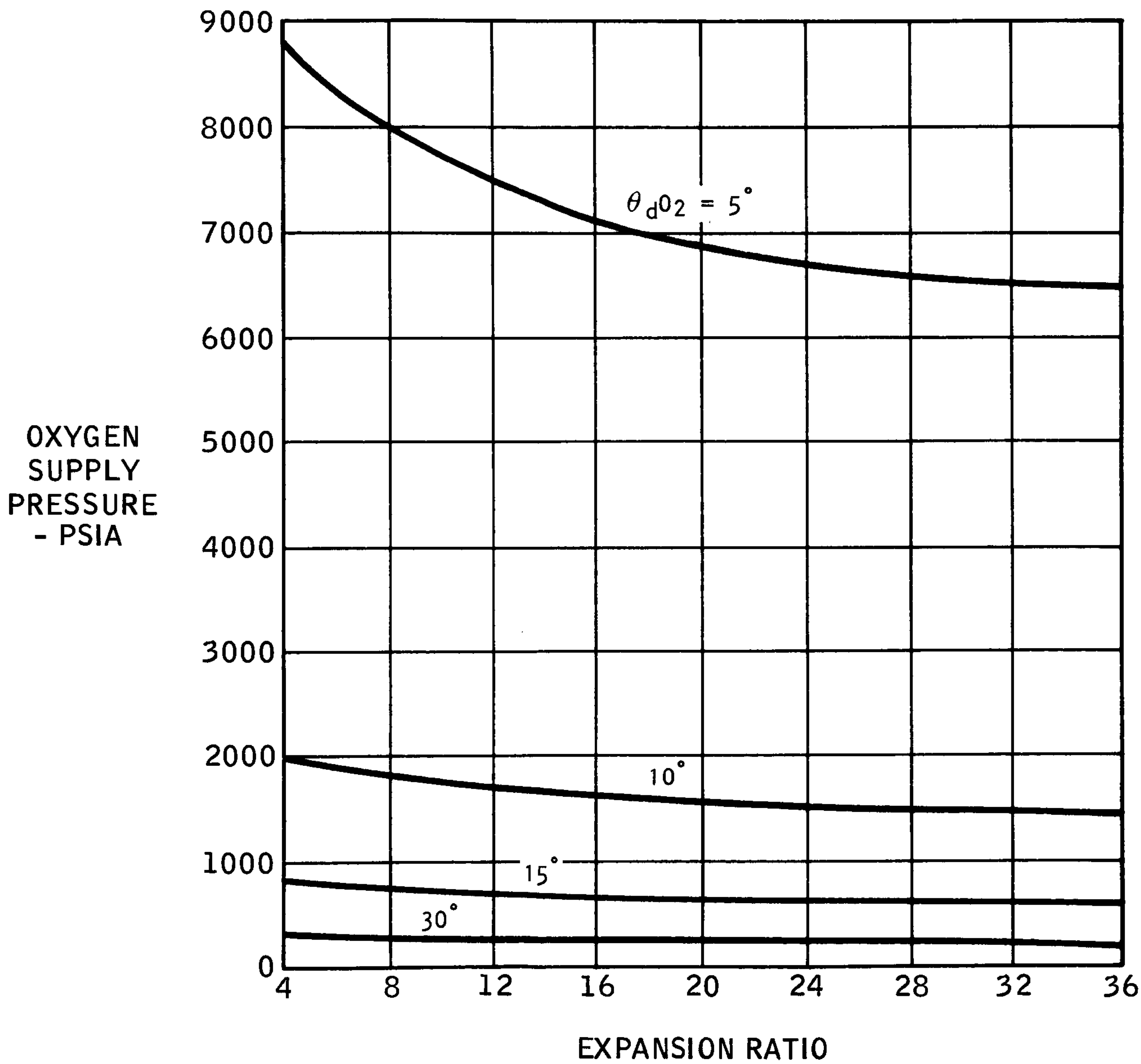

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Figure 15

Previous discussions have indicated the desirability of operating at high expansion ratios (viz: low admission ratios). To preclude combustion pressure buildup prior to termination of O_2 admission, the dwell angle should be minimized. Also, to eliminate the need for extreme pressure propellant storage facilities, the injection pressure of O_2 should be on the order of 1000 psi. Therefore, it is recommended that, for an admission equal to 0 (i.e., an expansion ratio of 36:1), dwell angle of 12° be adopted as the design point. Admission 12° BTDC is suggested. Sonic flow is assured, since the supply pressure for the O_2 is in excess of two times the pre-combustion pressure, P_1.

The H_2 supply pressures were calculated in much the same manner as the O_2 pressures. The same range of expansion and dwell were used. Results of the calculations are shown in Figure 16. The results are also similar to the O_2 case, in that as dwell angle decreases, pressure required increases, primarily because of the combined effects of smaller flow area and shorter opening duration per revolution. Pressure increases as expansion decreases because of the larger H_2 flow requirements resulting from the lower thermal efficiency at the higher admission values. For the 36:1 expansion ratio case, a dwell angle at 10° is recommended for preliminary engine tests at BMEP = 200 psi. Admission beginning 16° BTDC and terminating 6° BTDC is suggested.

Figures 17, 18 and 19 illustrate the effect of varying dwell angle and supply pressure on engine BMEP and RPM for the 36:1 expansion ratio case.

Any of the three modes of power modulation, variable pressure, variable dwell and variable O/F are practical. The choice can be made on a mechanical complexity and systems operation aspect.

HYDROGEN SUPPLY PRESSURE FOR BMEP = 200 PSI AT 3000 RPM

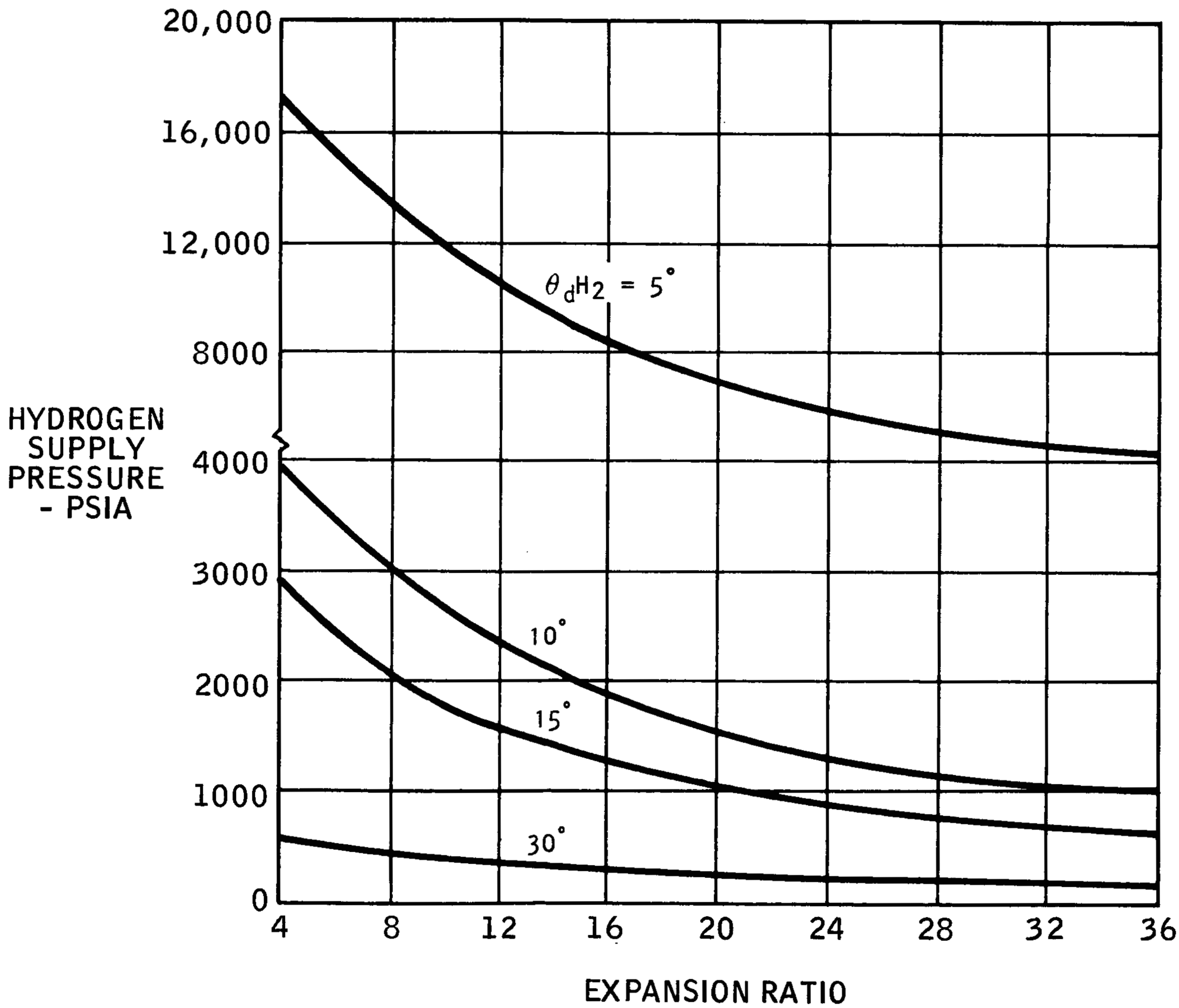

Figure 16

POWER MODULATION WITH CONSTANT DWELL & VARIABLE SUPPLY PRESSURE

O/F = 5.3
EXP. RATIO = 36
$\theta_d H_2 = 10°$
$\theta_d O_2 = 12°$

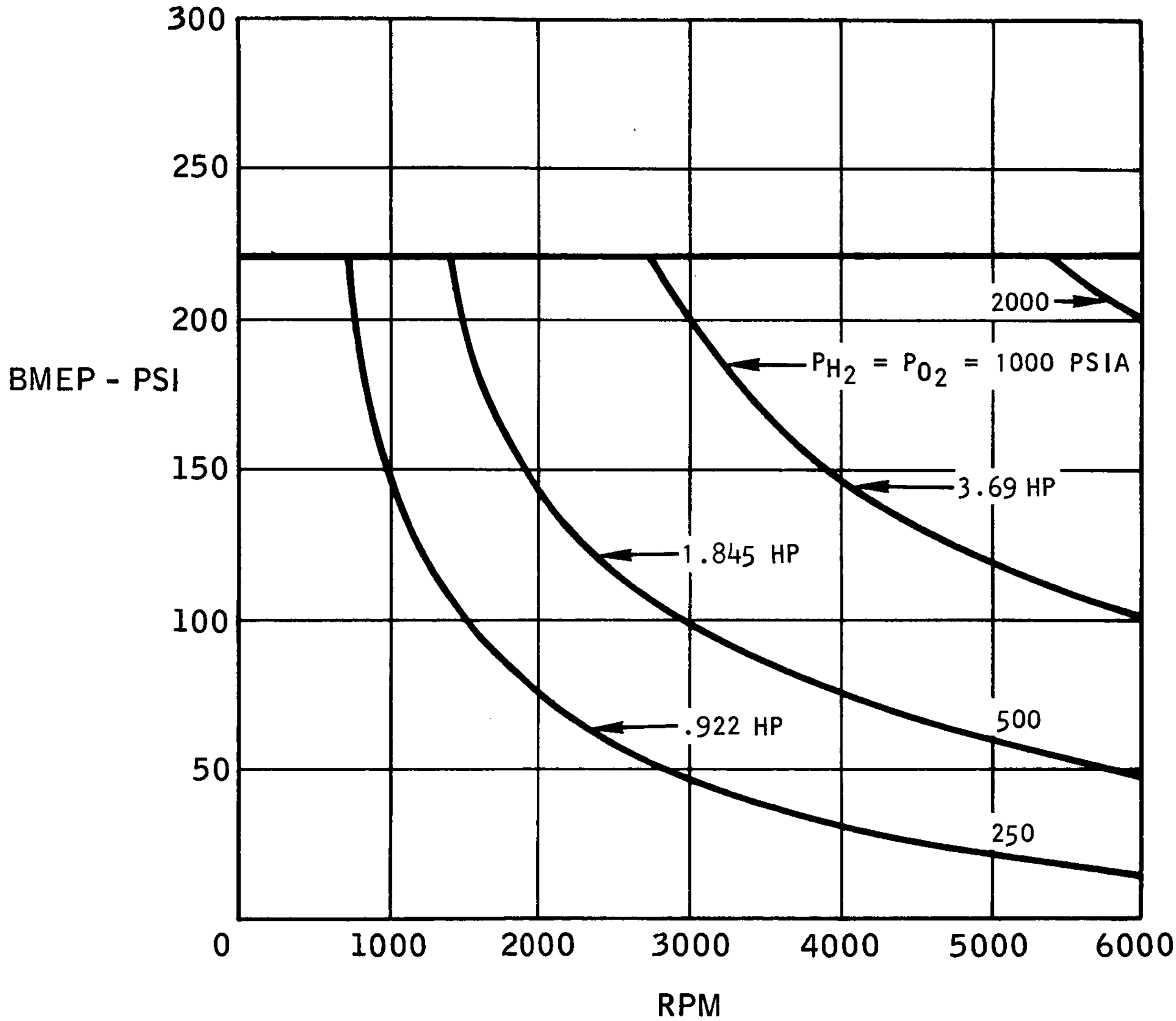

Figure 17

POWER MODULATION WITH CONSTANT SUPPLY PRESS & VARIABLE DWELL

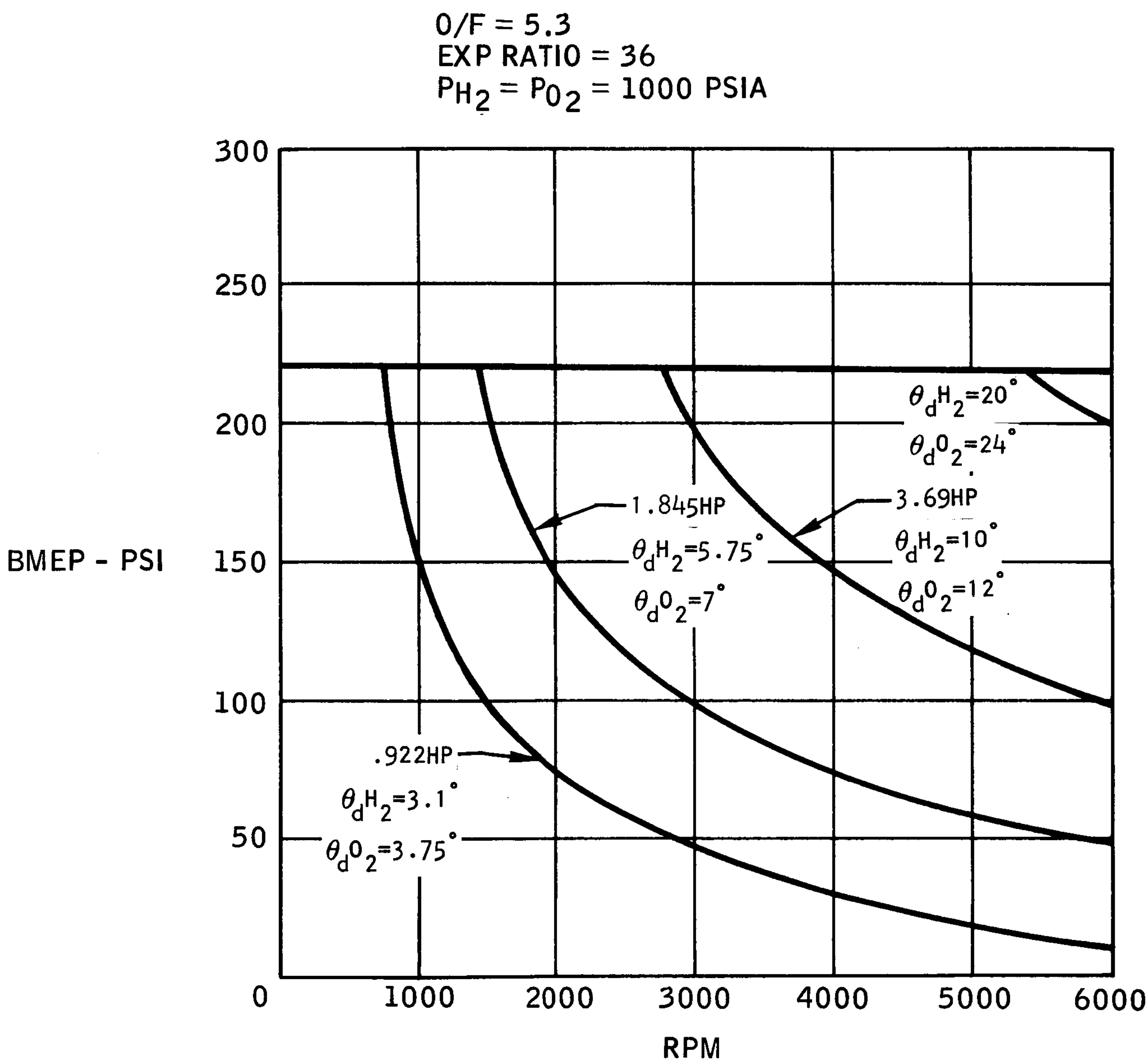

Figure 18

POWER MODULATION WITH CONSTANT SUPPLY PRESSURE & VARIABLE O/F

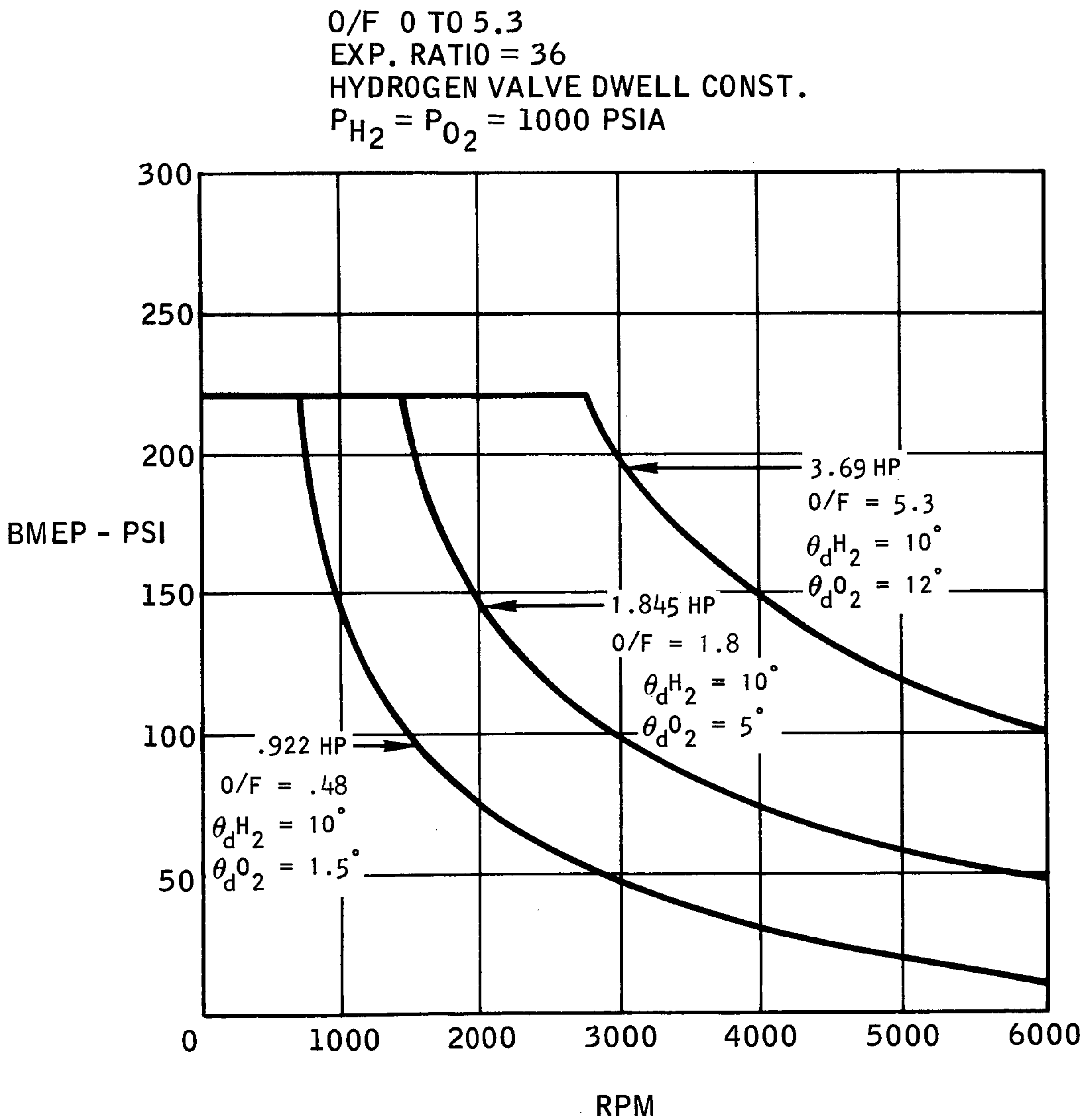

Figure 19

Definitions and Notations

BMEP	Brake mean effective pressure
BSPC	Brake specific propellant consumption
LHV	Lower heating valve
O/F	Oxidizer to fuel weight ratio
P_1	Pre-combustion pressure of H_2 and O_2 mixture
P_{H_2}	Pre-combustion partial pressure of hydrogen
Q	Heat rejection
r_e	Expansion ratio = $\frac{\text{volume after expansion when exhaust opens}}{\text{clearance volume}}$
W'	Propellant and tankage weight per horsepower-hour
Y	Algebraic factor Y = 0 when Q released at TDC Y = 1 when Q released after expansion
η_∞	Ideal thermal efficiency
η_x	Actual thermal efficiency
$\theta_d - H_2$	Hydrogen valve dwell (flow) angle
$\theta_d - O_2$	Oxygen valve dwell (flow) angle

APPENDIX A

PRESSURE - FLOW - DWELL RELATIONSHIPS

$$\dot{w}_{O_2} = \frac{3.88\ P_{T_{O_2}}\ \bar{A}\ C_o}{\sqrt{RT}} = \frac{3.88\ P_{T_{O_2}}\ \bar{A}\ (0.6)}{\sqrt{48.3 \times 520}}$$

Equiv. continuous weightflow through dwell valve

$$\dot{w}_{O_2} = \frac{\left(\dot{w}_{O_2} \sim \frac{lb}{hr}\right)}{3600} \frac{360}{\theta_d}$$

where θ_d is valve dwell angle

Equating the two above equations yields

$$P_{T_{O_2}} = \frac{6.8\ \dot{w}_{O_2}}{\theta_d\ \bar{A}} \quad \text{for choked flow}$$

similarly for H_2

$$P_{T_{H_2}} = \frac{27.1\ \dot{w}_{H_2}}{\theta_d\ \bar{A}}$$

where

w_{H_2} or $w_{O_2} \sim \frac{lb}{hr}$ (calculate from BSPC & O/F)

θ_d = degrees

$\bar{A}$ = average flow area - in^2 - see tab below

P_T = psia

Average flow area during dwell (based on 0.090 in. dia. injector orifice)

Dwell angle	A
5°	0.000875 in^2
10°	0.00194 in^2
15°	0.00316 in^2
30°	0.00442 in^2

APPENDIX B

SAMPLE ENGINE PERFORMANCE CALCULATION

Assume $T_3 = 2240° R$ (design limit)

$$r_e = \left(\frac{V_3}{V_c}\right) = \frac{2.057}{0.0572} = 36$$

$$\eta_\infty = 1 - \frac{1}{r_e^{\gamma-1}} = 1 - \frac{1}{(36)^{0.25}} = 0.592$$

$\eta_\infty = .592$
$\gamma = 0.6$
$\frac{Q}{HP} = 1.5$

$$\left(\frac{T_2}{T_1}\right)_{\text{usable for work}} = (36)^{0.25} = 2.45$$

$$T_2 \text{ usable} = 2.45\ (2240) = 5490° R$$

η_x

$$\Delta T_c = 5490 - 520 = 4970° R$$

Fig 12

From Figure ~~8~~, (O/F) ideal $= 3.35$?

For $\frac{Q}{HP} = 1.5$ at $Y = 0.6$ $\quad \frac{\eta_x}{\eta_\infty} = 0.63$

$$\eta_x = 0.63\ (\eta_\infty) = 0.63(0.592) = 0.372$$

$$(O/F)_{actual} = \frac{(O/F)_{ideal}}{\eta_x/\eta_\infty} = \frac{3.35}{0.63} = 5.32$$

Fig 5

From Figure ~~1~~, BSPC $= 1.28\ \frac{lb}{hp\text{-}hr}$?

Increase by 5% for leakage; thus

$$BSPC = 1.28 \times 1.05 = 1.34\ \frac{lb}{hp\text{-}hr}$$

4.0 PROGRAM PLAN

4.1 PROGRAM OBJECTIVE

The proposed 7 weeks program will be directed toward evaluating both analytically and experimentally the feasibility of operating the hypergolic ignition engine efficiently on hydrogen and oxygen propellants.

4.2 PROGRAM TASKS

Task 1 - Development Testing

Conduct a thermodynamic analysis of the engine operating on GH_2 and GO_2 propellants to determine the optimum selection of:

coolant temperature	expansion ratio
O/F ratio	injector orifice diameters
injector timing	ignition mechanism

Perform a design evaluation to establish the compatibility of the engine components and lubricants with H_2-O_2 and modify existing components of the SPU-2A-1 including the valve flow areas as necessary to permit satisfactory operation on GH_2-GO_2. Make the test setup and engine installation to document the following:

1. Engine rpm vs
   a. brake horsepower
   b. torque
   c. brake mean effective pressure
   d. brake specific propellant consumption
   e. thermal efficiency
   f. mechanical efficiency

2. Injection system performance
   a. Capability of handling GH_2 and GO_2 propellants
   b. Durability
   c. Control

3. Specific propellant consumption vs horsepower or brake mean effective pressure

4. Thermodynamic efficiency vs horsepower (or brake mean effective pressure)
5. Mechanical efficiency vs horsepower (or brake mean effective pressure)
6. Power at 3000 rpm as a function of O/F ratio and injection timing

Conduct tests with the SPU-2A-3 (Modified SPU-2A-1 for GH_2-GO_2) engine to verify feasibility of concept, performance and endurance. The testing will be organized into three groups as follows:

Cylinder Head Component Development Tests - Cold

Cylinder Head Assembly Development Tests - Hot

Engine Development Test

The cylinder head cold tests will determine injector valve calibration (flow vs valve position and flow vs rpm), and material suitability under a normal propellant environment. This procedure will allow evaluation of the valve assemblies without jeopardizing other engine components.

The cylinder head hot tests will determine propellant ignition characteristics at high $\triangle P$ pressures with the catalytic ignition source.

Engine development tests will establish the performance characteristics of the engine operating on GH_2 and GO_2 propellants. The parameters to be measured are listed above. Primary emphasis will be placed on determining the specific propellant consumption (SPC).

The test program will culminate in a 25 to 50 hour endurance run attempt as funding permits. The power level for this test shall be approximately 1/2 of the design power level and at a steady rpm. Following the test the engine will be completely disassembled and the condition of all parts evaluated. Specific emphasis will be given to the evaluation of wear characteristics of each component.

?

Task 2 - Reports

Prepare bimonthly letter reports covering all work accomplished during each two-week work period. Submit each report within 5 days following the end of the work period. Prepare a final report summarizing the results of the complete program and submit within thirty days following completion of the technical effort on the contract.

5.0 FACILITIES

5.1 GENERAL

The existing test facilities presently used for the hypergolic space power unit will be utilized for the SPU-2A-3 oxygen-hydrogen engine. A photograph of the test facility is shown in Figure 20. A major addition will be made to the existing test facilities for tankage, control and measurement of the flow rates of the hydrogen and oxygen propellants. The major components of the present facility are

1. The test stand with all necessary mounts for mechanical, electrical and instrumentation components.
2. An engine starting mechanism and power supply.
3. An engine power absorption unit.
4. A self-regulating engine cooling system.
5. A temperature regulated oil supply and scavenging system.
6. An exhaust ejector and altitude simulation system.

5.2 TEST FACILITY SUBSYSTEM DESCRIPTION

5.2.1 PROPELLANT SUPPLY SYSTEM

The test facility propellant supply system is shown schematically in Figure 21. This system is composed of high pressure gaseous hydrogen and gaseous oxygen supply tanks, a flow measuring system, and the necessary plumbing and control equipment to regulate the propellant supply to the engine. The propellant supply system also includes a very precise filtering system. Propellants entering the test engine are filtered to 1-1/2 micron absolute. The exhaust products from the engines are removed by a two-stage steam ejector system. This system is capable of continuous operation at 0.5 psia when the SPU-2A-3 test engine is operating at maximum power and rpm.

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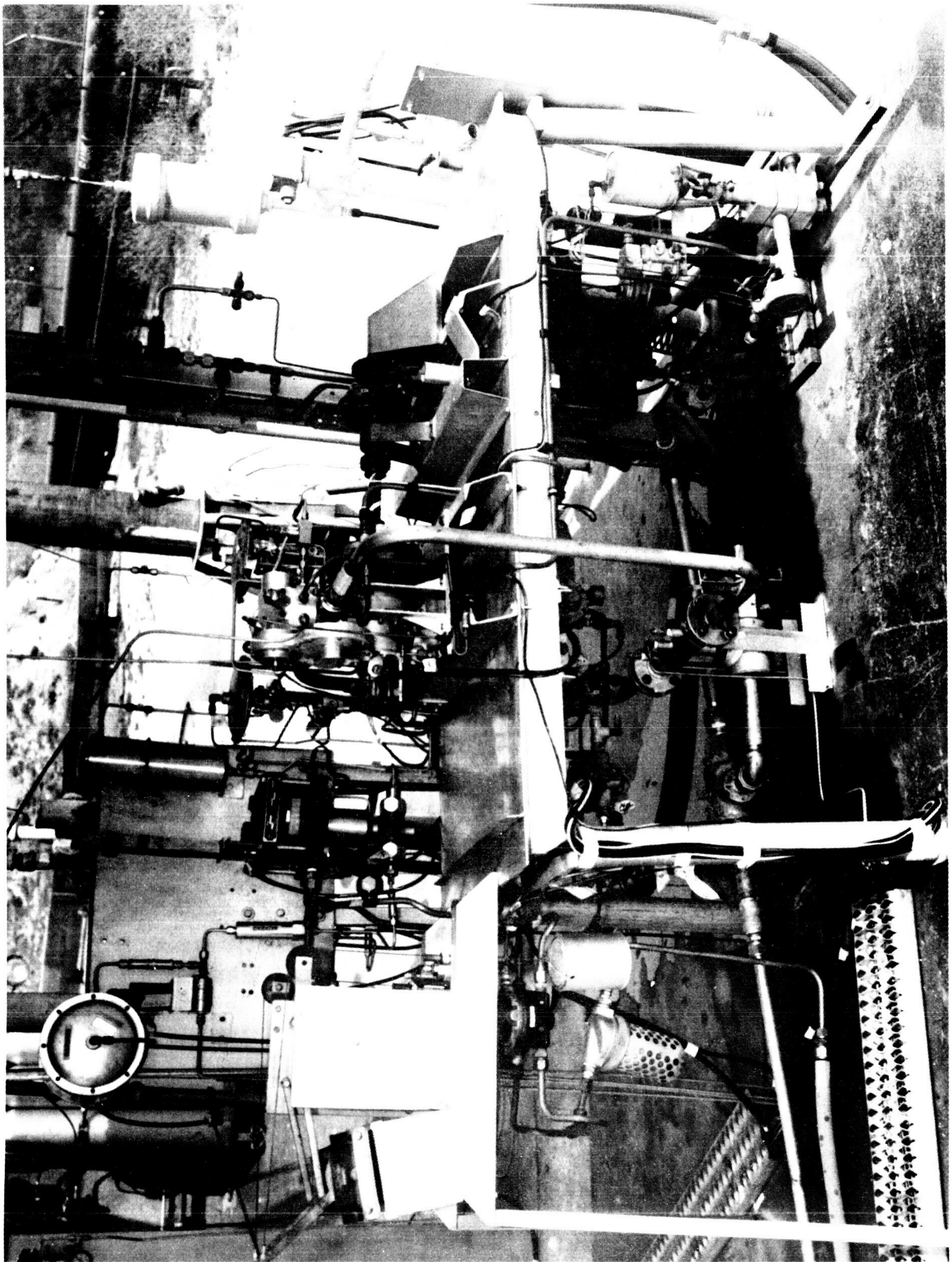

SPU-2A-1 Engine Installed in the Test Facility

1-1257

Figure 20

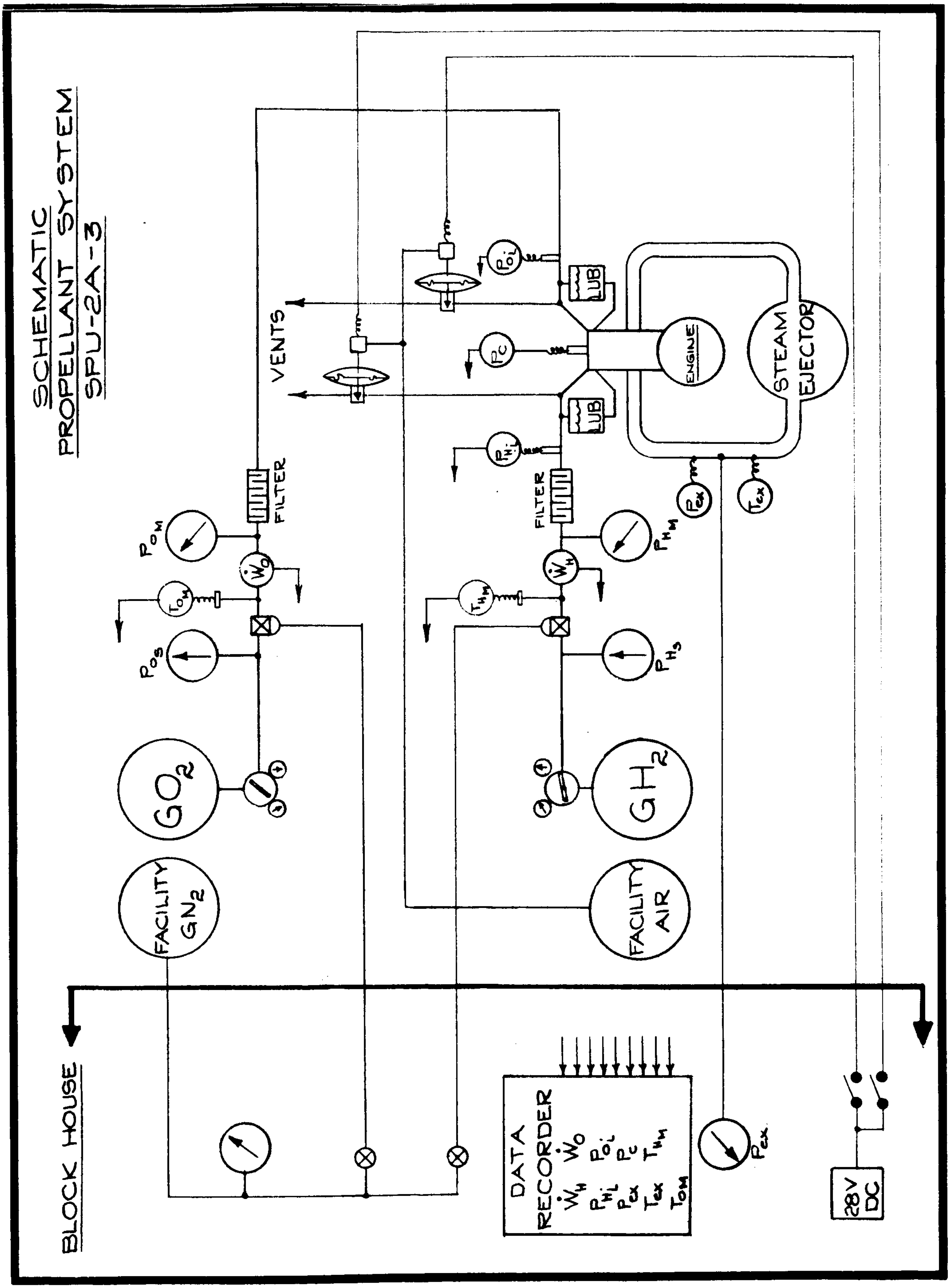
SCHEMATIC
PROPELLANT SYSTEM
SPU-2A-3
VENTS
FILTER
FILTER
LUB
LUB
ENGINE
STEAM EJECTOR
GO2
GH2
FACILITY GN2
FACILITY AIR
BLOCK HOUSE
DATA RECORDER
28V DC

Figure 21

5.2.2 COOLING SYSTEM

A schematic of the cooling system is presented in Figure 22. This system automatically regulates the inlet coolant temperature at any temperature between ambient and 200° F. In addition to temperature regulation, the flow rate of coolant is also adjustable over a broad flow range. The cooling system is actuated during engine startup and will maintain preset conditions of flow (0.1 to 5.0 GPM) and inlet temperatures (ambient to 200° F for water). An automatic overtemperature control system is provided. This system will actuate if the coolant exit temperature exceeds a preset value, normally 170°, and will bias the inlet temperature regulator and reduce the inlet coolant temperature until the high exit temperature is corrected. Heat influx to the coolant is accurately determined by the flow and temperature instrumentation.

5.2.3 OIL SYSTEM

The oil system is composed of a tank complete with temperature control, a high pressure pump, a low pressure high volume scavenge pump, two micron filter and the necessary plumbing and control components. This system is shown schematically in Figure 23. This system is capable of handling both petroleum and synthetic lubricants.

5.2.4 DRIVE SYSTEM

The drive system is composed of three major elements, a starting system, a torque absorption unit (dynamometer), and a crankshaft position indicator. A system schematic is shown in Figure 24. The starting system is a 12 volt starter motor transmitting rotation via an overruning clutch to the engine. The water dynamometer provides accurately controllable absorption of power and speed of 15 horsepower and 10,000 rpm respectively. To facilitate engine testing, the dynamometer is precalibrated with fixed restricters in the dynamometer water inlet line. Several restricters were calibrated and made available to form a valve tree. Location of this tree relative to the dynamometer system is shown in the schematic. Figure 24,

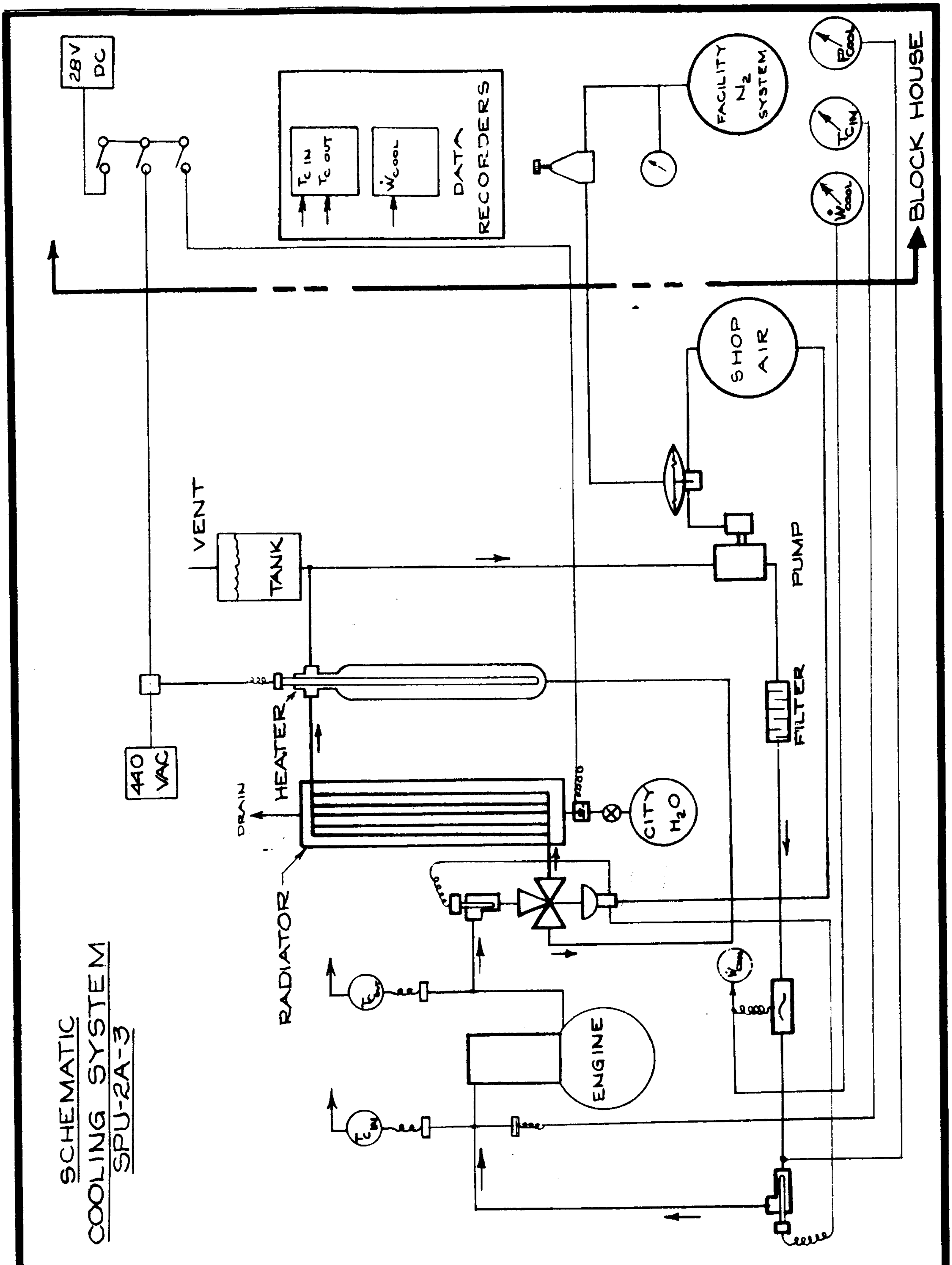
SCHEMATIC
COOLING SYSTEM
SPU-2A-3
28V DC
T_C IN
T_C OUT
$\dot{W}_{COOL}$
DATA RECORDERS
FACILITY N_2 SYSTEM
BLOCK HOUSE
SHOP AIR
VENT
TANK
PUMP
FILTER
HEATER
440 VAC
DRAIN
RADIATOR
CITY H_2O
ENGINE

Figure 2

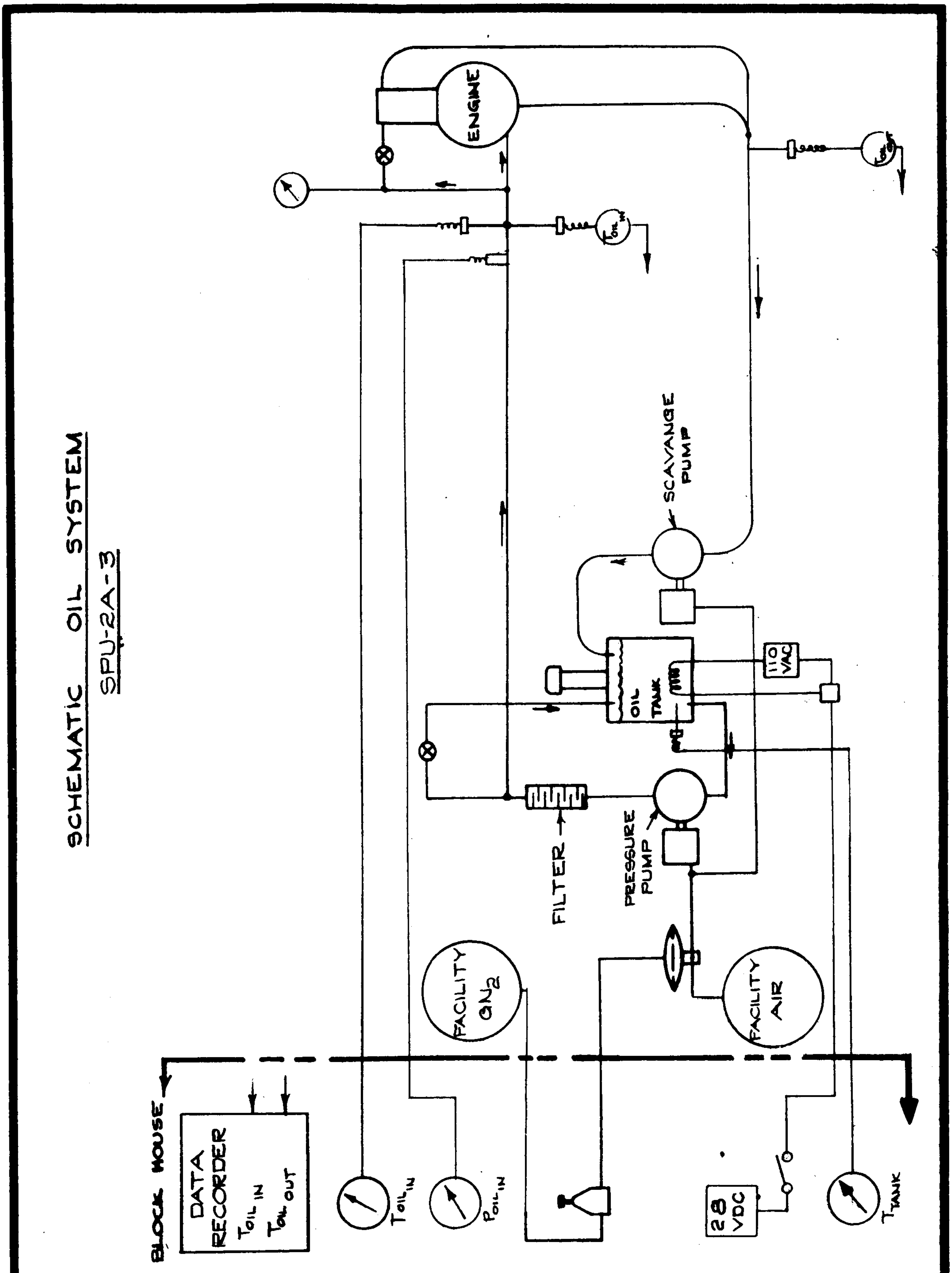
SCHEMATIC OIL SYSTEM
SPU-2A-3
ENGINE
SCAVANGE PUMP
OIL TANK
110 VAC
FILTER
PRESSURE PUMP
FACILITY GN2
FACILITY AIR
BLOCK HOUSE
DATA RECORDER
T OIL IN
T OIL OUT
T OIL IN
P OIL IN
28 VDC
T TANK

Figure 23

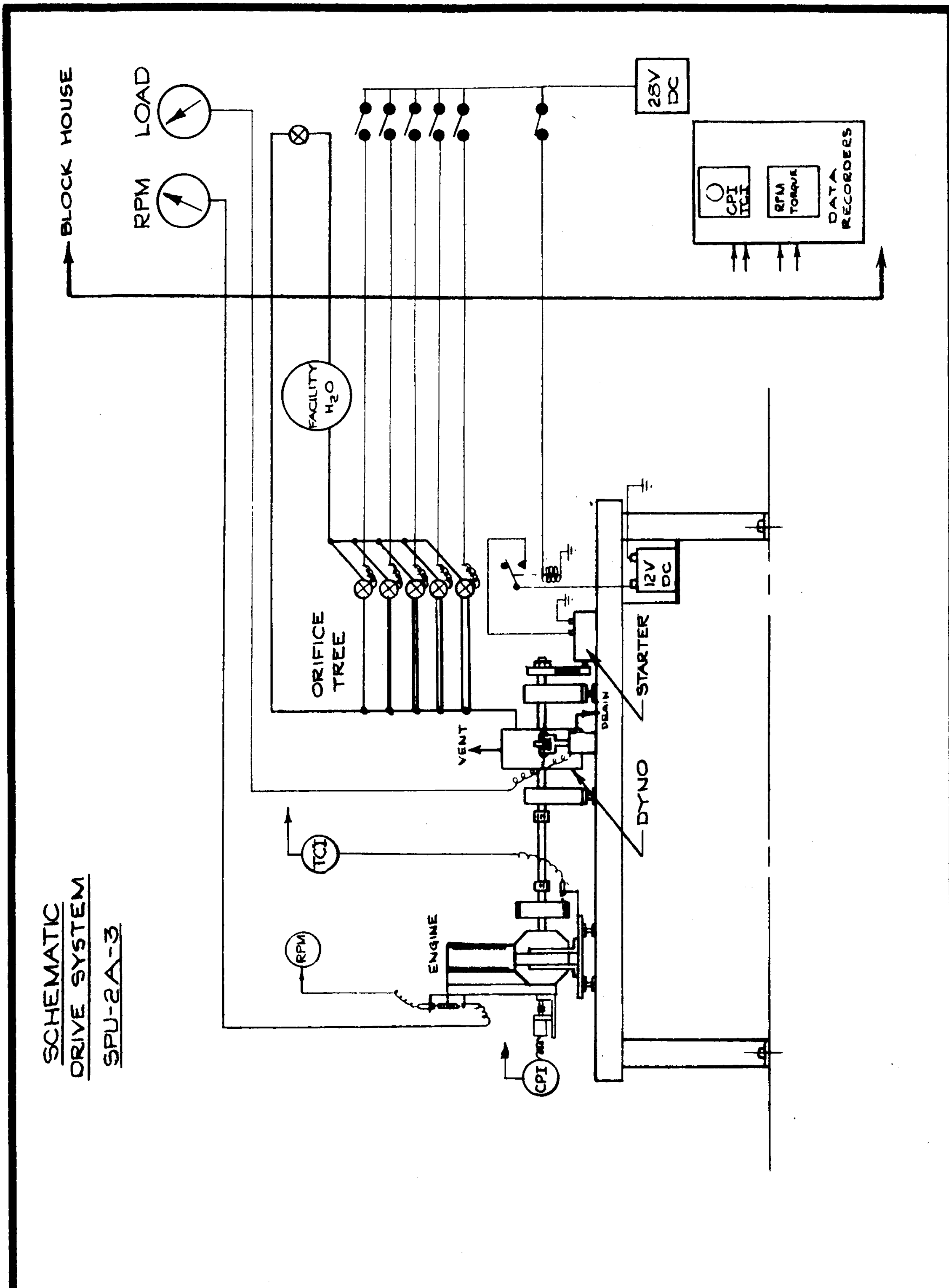
SCHEMATIC
DRIVE SYSTEM
SPU-2A-3
BLOCK HOUSE
RPM
LOAD
28V DC
CPI
TCI
RPM
TORQUE
DATA RECORDERS
FACILITY H_2O
ORIFICE TREE
12V DC
STARTER
DRAIN
VENT
DYNO
TCI
ENGINE
RPM
CPI

Figure 24

The crankshaft position indicator is a rotary potentiometer capable of being driven at high rotative speeds. This device is attached to the crankshaft of the test engine and when used in conjunction with the cylinder pressure transducer and oscilloscope will produce an enclosed pressure vs position diagram. These data are recorded photographically for later reduction into a pressure vs volume plot.

5.2.5 INSTRUMENTATION

The instrumentation provided to document engine performance is shown in Figure 25. The instrumentation list is divided into visual and recorded sections. The visual instrumentation operates continuously during engine operation to allow precise setting of engine run conditions and manual recording of performance parameters. The recorded data system operates continuously during short engine test periods or intermittently utilizing the random sampling technique during long duration engine testing. The location of each transducer etc., necessary to produce the required data are shown on the various system schematics, Figures 21 thru 24.

5.2.6 COMPONENT TEST CAPABILITY

In addition to support, control, and documentation of full-scale engine operation, the Test Facility has the capability of testing engine components and subsystems. The basic facility is augmented with additional mounts and drive systems for dynamic injector valve development testing such as required in phases I and II of the test program. The cylinder head assembly of the SPU-2A-3 engine can be mounted on the test pad and supplied with propellants from the facility propellant system and can be driven at speeds up to 5600 rpm with a remotely actuated air drive motor system. The drive system is equipped with a torque limit to preclude damage to the test item components in the event of a component malfunction. The many hours of component test utilizing the facilities subsystems previously have afforded the opportunity to resolve support system problems and allow a high degree of confidence in the ability of the test facility to perform satisfactorily the job it was designed to accomplish.

SPU-2A-3 INSTRUMENTATION

Parameter	Symbol	Range	Display Method Recorded	Display Method Visual
1. Combustion Chamber Pressure	P_c	0-3000 psi	x	
2. Crank Position Indicator	CPI	0-360°	x	
3. Top Center Indicator	TCI	NA	x	
4. Engine Speed	RPM	0-6000 RPM	x	x
5. Engine Load	L	0-20 lb	x	x
6. Facility GN_2 Pressure	P_{N_2}	0-1000 lb		x
7. Oxygen Tank Pressure	P_{o_t}	0-2500 psi		x
8. Hydrogen Tank Pressure	P_{h_t}	0-2500 psi		x
9. Oxygen Supply Pressure	P_{o_s}	0-6000 psi		x
10. Hydrogen Supply Pressure	P_{h_s}	0-6000 psi		x
11. Oxygen Manifold Pressure	P_{o_m}	0-4000 psi		x
12. Hydrogen Manifold Press.	P_{h_m}	0-4000 psi		x
13. Oxygen Injection Pressure	P_{o_i}	0-4000 psi	x	
14. Hydrogen Injection Press.	P_{h_i}	0-4000 psi	x	
15. Exhaust Manifold Press.	P_{e_x}	0-1 Atmos.	x	x
16. Oil Manifold Pressure	$P_{oil_{in}}$	0-75 psi		x
17. Cylinder Head Oil Pres.	$P_{cyl_{in}}$	0-20 psi		x

Figure 25

SPU-2A-3 INSTRUMENTATION
(Continued)

Parameter	Symbol	Range	Display Method Recorded	Display Method Visual
18. Coolant Pressure	P_{cool}	0-30 psi		x
19. Oxygen Flow Rate	$\dot{W}_o$	0-10 lb/hr	x	x
20. Hydrogen Flow Rate	$\dot{W}_h$	0-10 lb/hr	x	x
21. Coolant Flow Rate	$\dot{W}_{cool}$	0.1 - 1.0 GPM	X	x
22. Exhaust Temperature	T_{ex}	0-2000°F	x	
23. Oxygen Manifold Temp.	T_{om}	0-500°F	x	
24. Hydrogen " "	T_{hm}	0-500°F	x	
25. Oil Inlet Temp.	$T_{oil_{in}}$	0-250°F	x	
26. Oil Outlet Temp.	$T_{oil_{out}}$	0-250°F	x	
27. Oil Tank Temp.	T_{Tank}	0-250°F		x
28. Coolant Inlet Temp.	$T_{c_{in}}$	0-250°F	x	x
29. Coolant Outlet Temp.	$T_{c_{out}}$	0-250°F	x	

Figure 25 (Continued)

6.0 PROGRAM MANAGEMENT

6.1 ORGANIZATION

The program will be accomplished in the Power Systems Division of The Marquardt Corporation. This Division is a fully integrated organization specializing in the management of research and development type contracts, including the necessary support groups.

6.2 DEPARTMENT ORGANIZATION

The work proposed will be performed in the Space Equipment Group, a section of the Advanced Product Development Department. The functional relationship of this department to the Corporate organization is shown by Figure 26. The Space Equipment Group is staffed with senior engineers and scientists who are experienced in advancing the state-of-the-art by basic analysis and experimental development.

6.3 PROGRAM ORGANIZATION

The program will be organized on a project basis. The Program Manager, Mr. J. R. Kessler, will be responsible for the over-all program including: plans, schedules, and budgets necessary for the successful accomplishment of the program objectives. He will represent the company in technical discussions with the customer and will be responsible for issuing work orders and for integrating and coordinating the efforts of other company organizations contributing to the over-all program. The Project Engineer, Mr. M. Arao will be responsible for technical implementation of the program, including analysis, design and development.

The project organization proposed for the extended GH_2-GO_2 Engine Space Power System program is illustrated by the boxed in area on the ensuing Figure 14.

ORGANIZATION CHART

SHOWING RELATIONSHIP TO CORPORATE STRUCTURE

AND FUNCTIONAL RELATIONSHIP TO THE MANNED SPACECRAFT CENTER

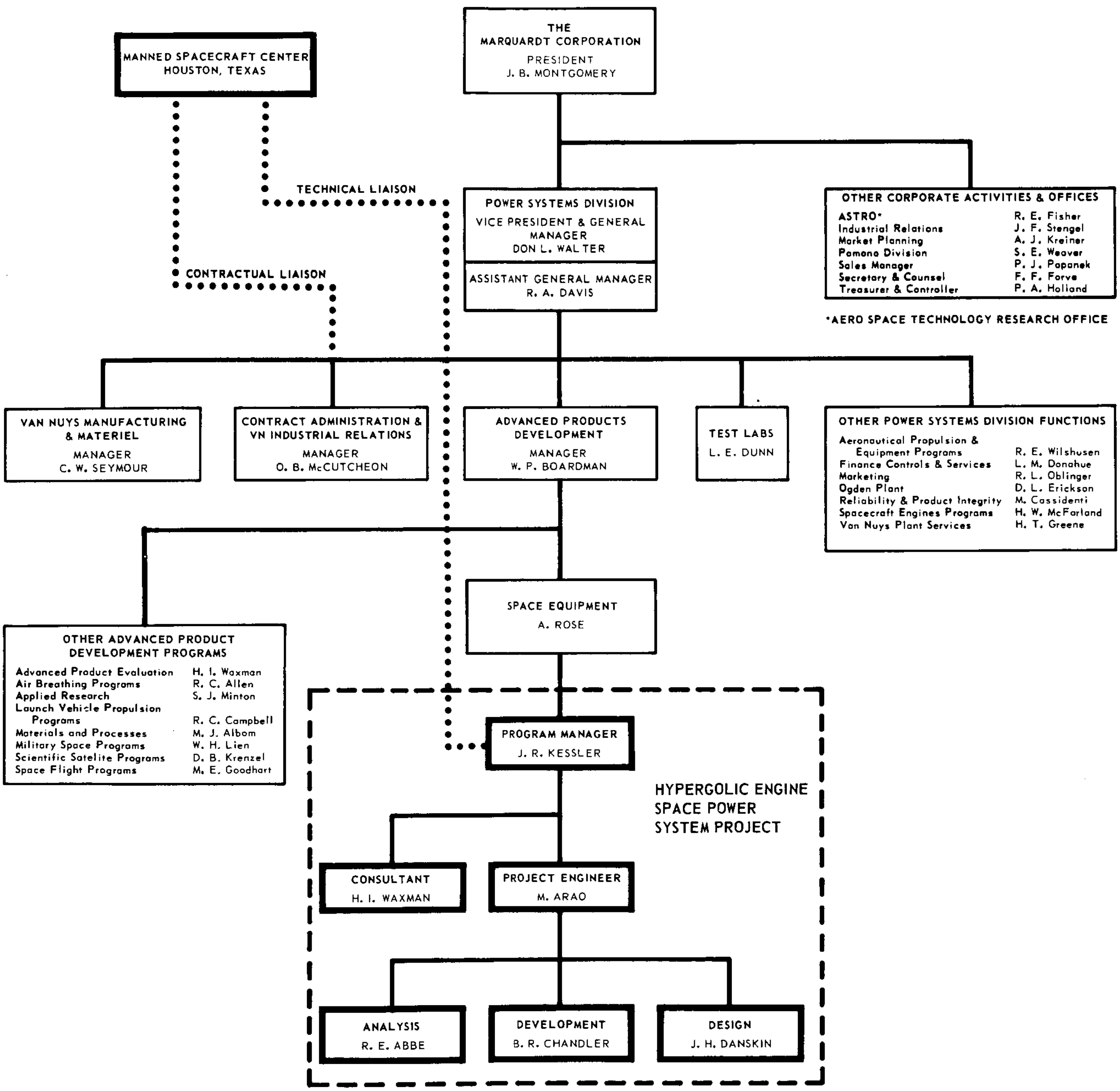

Figure 26